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4th International Conference on Sustainable Futures: Environmental, Technological, Social and Economic Matters

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4th International Conference on Sustainable Futures: Environmental, Technological, Social and Economic Matters

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Abstract. This paper presents the preface of the proceedings for the 4th International Conference on Sustainable Futures: Environmental, Technological, Social, and Economic Matters (ICSF 2023), a multidisciplinary event that explores the challenges and opportunities of sustainability in various domains. The preface outlines the conference's objectives, themes, workshops, and topics, as well as its contribution to advancing sustainable development and global dialogue. It also acknowledges the efforts and inputs of various stakeholders who have made the conference possible, especially in light of the pandemic situation. Furthermore, it thanks IOP Publishing for its support and flexibility in facilitating open access publishing. The paper concludes by looking forward to future editions of ICSF and the ongoing quest for a more sustainable and interconnected world. The paper invites readers to delve into the rich and diverse content that shapes this influential conference.

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1. Introduction

Welcome to the **International Conference on Sustainable Futures: Environmental, Technological, Social, and Economic Matters** (**ICSF**) proceedings. This conference serves as a cornerstone for global discourse on sustainable development, providing a peer-reviewed international platform where researchers, scientists, engineers, and practitioners converge to share their latest research findings, innovative ideas, and practical applications. As we delve into these proceedings, we embark on a journey across diverse disciplines, united by a common goal of advancing sustainable practices.

Figure 1 showcases the emblem of ICSF 2023, a symbol of our collective commitment to fostering sustainable futures.

Figure 1. The emblem of ICSF 2023.

Since its inauguration in 2020, ICSF has cultivated a space that encompasses the entire spectrum of sustainable development. With a focus on the intricate intersections of sustainability, environment, and technology, ICSF explores their far-reaching implications for corporations, governments, educational institutions, regions, and societies, both in the present and the future [1–4].

ICSF 2023 stands as a two-tiered platform, comprising pre-conference workshops and the main conference, ensuring an enriched experience for all participants.

The subsequent sections delve into the diverse workshops that comprised ICSF 2023:

The *Sustainable Development of Mining Science and Industry Workshop* (SusDevMiningScI'2023) stands as a peer-reviewed international forum dedicated to exploring cutting-edge scientific and technological achievements in mine safety, geological research, and the preservation of mineral resources. With a focus on topics spanning mining subsurface exploration, mining systematology, and geotechnical engineering, this workshop underlines our commitment to sustainable practices. Dr. Serhii Chukharev leads the program committee, guiding these vital discussions.

Workshop URL: `https://sites.google.com/knu.edu.ua/nigri-ecochemsd-ws2023/`.

1.1. Geography for Sustainable Development (GSD-2023)

Geography for Sustainable Development (GSD-2023) serves as a peer-reviewed international workshop, offering a platform for researchers deeply engaged with the challenges of sustainable development within the geographical context. Covering an array of topics, including biogeochemical cycles, climate, natural resources, and more, this workshop is a testament to the expansive scope of geography's role in shaping sustainable futures. Dr. Olga Bondarenko guides these explorations through her leadership.

Workshop URL: `https://bondarenkoolga9.wixsite.com/gsd-2023`.

1.2. Ecochemistry for Sustainable Development (EcoChemSD-WS'2023)

The *Ecochemistry for Sustainable Development Workshop* (EcoChemSD-WS'2023) operates as a peer-reviewed international gathering, nested within the 4th International Conference on Sustainable Futures: Environmental, Technological, Social, and Economic Matters (ICSF). This workshop engages with the multidimensional aspects of environmental chemistry, ecochemistry, and their resonance within fields such as geochemistry, agroecology, and green chemistry. Dr. Pavlo Nechypurenko spearheads these discussions, forging pathways towards sustainable chemical practices.

Workshop URL: `https://sites.google.com/view/ecochemsd-ws2023`.

1.3. Biodiversity and Ecosystems Sustainability (BiodES-2023)

Biodiversity and Ecosystems Sustainability (BiodES-2023) stands as a peer-reviewed international workshop, lending its focus to the critical task of conserving biodiversity and fostering ecosystem sustainability. Rooted in applied science and education, this workshop offers a vital foundation for addressing global challenges and nurturing sustainable futures. Dr. Viacheslav Osadchyi leads the charge in exploring the intersection of environmental, technological, and biological aspects in this context.

Workshop URL: `http://biodes.mdpu.org.ua/`.

1.4. Water Management and Environmental Engineering (WaterManEnvE-2023)

The *Water Management and Environmental Engineering Workshop* (WaterManEnvE-2023) stands as a peer-reviewed international platform, encapsulating contributions that span the breadth of water management, environmental engineering, and educational technologies. With a focus on topics including water resources, irrigation, hydraulic engineering, and more, this workshop navigates the complexities of managing our most precious resource sustainably. Dr. Serhii Klimov provides direction for these explorations.

Workshop URL: `https://sites.google.com/nuwm.edu.ua/watermanenve-ws2023/`.

1.5. Innovative Approaches for Solving Environmental Issues (IASEI-2023)

Innovative Approaches for Solving Environmental Issues (IASEI-2023) converges as a peer-reviewed international workshop, focusing on advancing environmental science research. Covering topics ranging from environmental protection to nuclear safety and technological solutions, this workshop embodies the spirit of pioneering solutions for pressing environmental challenges. Dr. Andrii Iatsyshyn leads the charge in cultivating innovative discussions.

Workshop URL: `https://www.igns.gov.ua/en/iasei-ws-2023/`.

1.6. Sustainable Energy Workshop (SEnW-2023)

Sustainable Energy Workshop (SEnW-2023) embarks on an exploration of innovative solutions in energy systems. Covering a diverse array of topics including solar and wind energy, energy policy, climate change, and more, this workshop underlines the essential role of sustainable energy in shaping our future. Guided by Dr. Volodymyr Artemchuk, this workshop paves the way for sustainable energy practices.

Workshop URL: `https://ipme.kiev.ua/en/SEnW-2023/`.

1.7. Conference sessions

The conference unfolded through a series of sessions, each shedding light on different facets of sustainable development. These sessions encompassed topics ranging from sustainable materials and technologies to socio-economic development, energy systems, and beyond. These sessions, as detailed below, comprised the backbone of ICSF 2023:

Session 1. Sustainable Materials and Technologies (May 23, 2023)
Session 2. BiodES-2023 – Biodiversity and Ecosystems Sustainability. Sustainability, Biodiversity and Conservation (May 23, 2023)
Session 3. SEnW-2023 – Sustainable Energy Workshop. Sustainable Energy. Infrastructure and Sustainability (May 23, 2023)
Session 4. SusDevMiningScI'2023 – Sustainable Development of Mining Science and Industry. Geotechnical and Geoenvironmental Engineering. Sustainable Mining (May 23, 2023)
Session 5. Sustainable Building and Architecture. Sustainable Cities and Society (May 24, 2023)
Session 6. WaterManEnvE-2023 – Water Management and Environmental Engineering. Environmental Engineering, Sustainability, and Green Technology (May 24, 2023)
Session 7. EcoChemSD-2023 – Ecochemistry for Sustainable Development. Sustainable Use of Natural Resources (May 24, 2023)
Session 8. IASEI-2023 – Innovative Approaches for Solving Environmental Issues. Environmental Pollution and Sustainable Development. Environmental Risk Assessment and Sustainable Development. Sustainable Environment and Environmental Management (May 24, 2023)
Session 9. Sustainable Socioeconomic Development. Governance, Legislation and Policy for Sustainability (May 25, 2023)
Session 10. GSD-2023 – Geography for Sustainable Development. Agroecology and Sustainable Food Systems. Geography and Sustainability. Sustainable Transport (May 26, 2023)

This volume is a repository of the scholarly contributions presented at ICSF 2023. With meticulous reviews conducted by a minimum of three program committee members, the selected papers embody the spirit of rigorous exploration and discovery.

Authors were invited to submit full research papers including surveys, tutorials, perspective/colloquia articles in conference topics of interest (`https://www.morressier.com/call-for-papers/62c564c8178bca0013ca7d13`). There were 243 submissions received. Each submission was reviewed by at least 3 program committee members. The committee decided to accept 147 papers.

The unfolding events of the ongoing Russian invasion of Ukraine necessitated a hybrid conference format. By embracing both in-person and online modes, ICSF 2023 extended its reach across borders, allowing more than 200 participants from 18 countries to participate through platforms such as Zoom and Google Meet.

The presentation slots were defined as follows:

- invites talks (25 min): 15 min presentation, 10 min question answering and discussion,

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- other talks (15 min): 10 min presentation and 5 minutes question answering and discussion.

The full ICSF 2023 program is available at the https://icsf.ccjournals.eu/2023/ where details of the sessions, usually headed by one or more invited presentations. Video records of talks are available at the *Not So Easy Science* YouTube channel (https://www.youtube.com/channel/UCH3gego79m-ofCiNEgEzMuA).

2. ICSF 2023 program committee

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3. ICSF 2023 organizers

The 4th edition of the International Conference on Cognitive and Natural Sciences (ICSF) was meticulously coordinated by the Academy of Cognitive and Natural Sciences (ACNS), a non-governmental organization dedicated to nurturing the growth of researchers' expertise in the cognitive and natural sciences arena. ACNS's mission encompasses enhancing research, safeguarding rights and liberties, and catering to professional, scientific, social, and various other interests.

ACNS is engaged in a spectrum of activities, including:

- Spearheading research initiatives within the cognitive and natural sciences domain and fostering collaborative ties among researchers [124, 125].

- Orchestrating conferences, workshops, training sessions, internships, and other platforms for the exchange and dissemination of knowledge in the realm of cognitive and natural sciences [126, 127].
- Publishing scientific journals, conference proceedings, collections of scholarly works, and related materials (`https://acnsci.org/cms/journals/`).

Among ACNS's prominent publications is the Diamond Open Access journal titled *Educational Technology Quarterly* (ETQ) [128], a peer-reviewed journal delving into the ways digital technology can enrich the field of education. Notably, ETQ covers a broad range of topics aligned with the Sustainable Development Goals (SDGs), with the exception of Goal 4 – Quality Education.

Here are select topics from *Educational Technology Quarterly* (ETQ) categorized by SDG goals:

SDG 3 (Good Health and Well-being)
- Addressing continuing education during the pandemic and preparing children for STEAM education, aligning with health and education goals [129].
- Examining the well-being of employees during remote work and the impact of stress on their mental health [130].
- Exploring the use of cloud technologies in education during the COVID-19 pandemic, potentially enhancing education and well-being [131].
- Enhancing physical education teachers' competency in health preservation, contributing to improved well-being [132].
- Investigating the use of virtual reality in education to improve student health and learning outcomes [133].

SDG 8 (Decent Work and Economic Growth)
- Aligning educational programs with real-life job requirements to ensure quality education and employability [134].
- Enhancing education and career guidance through innovative digital solutions [135].

SDG 9 (Industry, Innovation, and Infrastructure)
- Improving infrastructure and technological innovation in education [136].
- Enhancing education quality and integrating digital tools, aligning with education and technological innovation goals [137].
- Elevating the quality of education and enhancing technology infrastructure for software engineering education [138].
- Elevating the quality of physics education (STEM) through blended teaching methods and technology integration [139].
- Developing academic cloud infrastructure and integrating innovative technology platforms to improve education quality [140].
- Enriching the learning environment through digital transformation and innovative technologies [141, 142].
- Enhancing the quality of distance education through expert examination and training programs for course developers [143].
- Leveraging innovative technologies like augmented reality to enhance language education [144].
- Analyzing the impact of digital disruption on education and business continuity, aligning with improving education quality and technological innovation [145].
- Utilizing online courses to enhance programming education and promote innovation in education [146].

- Creating an educational encyclopedia to disseminate verified knowledge, promoting education quality and innovation [147].
- Enhancing education quality and innovation through virtual labs [148].
- Integrating STEM education and technology, aligning with educational quality and innovation goals [149].

SDG 15 (Life on Land): Utilizing plant recognition systems to support environmental awareness and conservation efforts [150].

SDG 16 (Peace, Justice, and Strong Institutions): Monitoring and countering negative psychological influences, which might promote peace and well-being [151].

4. Proceedings structure

4.1. Advancements in materials science and engineering for sustainable development

This proceedings section delves into the realm of materials science and engineering, unveiling a tapestry of innovative research endeavors aimed at fostering sustainable development. The featured studies collectively showcase the intricate relationship between material composition, quality, and their impact on various industrial processes and applications [152]. From investigating the role of lime content in iron ore sintering [153] to the sustainable performance of alkali-activated cement concrete with exceptional freeze-thaw resistance [154], the range of topics traverses the spectrum of material behavior and application.

The section delves into the realm of alternative materials, exploring sustainable modified pozzolanic supplementary cementitious materials harnessed from natural zeolite, fly ash, and silica fume [155]. Furthermore, it presents a meticulous balance between theoretical and practical aspects, with research on the stress-strain state of compressed concrete-filled steel tube elements [156] and the influence of deformation degree on grain sizes in metal alloys during cold rolling of sheets [157].

Innovation takes center stage with studies on robust methods for controlling casting processes and casting quality [158], as well as the technology behind forming wear-resistant thermite alloy layers through high-temperature synthesis [159]. The intersection of material science and medical applications is also explored, as evidenced by the design and research of biologically active polymeric hydrogel transdermal materials modified by humic acid [160].

Electromagnetic radiation protection finds a place in this collection, focusing on ceramic-inorganic polymer composites that harmonize mechanical properties with efficient electromagnetic shielding [161]. The section also touches upon the evolving energy landscape, offering insights into enhancing the discovery and storage of natural gas deposits [162], including improvements in drilling mud and terrestrial storage-shelter facilities [163].

In essence, this proceedings section encapsulates the pioneering strides made within materials science and engineering, underscoring their pivotal role in realizing sustainable development goals across a diverse range of sectors and applications. The studies presented here illuminate the path toward a more resilient and resource-efficient future.

4.2. Ecological dynamics and biodiversity assessment in changing environments

This section of the proceedings unveils a diverse array of studies centered around the intricate interplay between ecological dynamics and biodiversity assessment within evolving environments. The talks featured here encapsulate the multifaceted nature of environmental changes and their profound impact on various facets of ecosystems.

Exploring the ecomorphic aspect of soil macrofauna community transformation under recreational impact [164], the section kicks off by delving into the intricate relationships between human activities and the delicate balance of terrestrial ecosystems. Moving forward, biocenotic influence takes the spotlight as researchers investigate the role of the great cormorant in shaping the Azov-Black Sea region's biodiversity [165].

The section transcends traditional boundaries by addressing the accumulation of endocrine-disrupting compounds in aquatic organisms, offering insights into the potential ecological and hygienic implications of pollutant accumulation in Procambarus Virginalis tissue from the Dnipro River [166]. Biodiversity assessment within the Danube region emerges as a pivotal tool for the development of protected areas [167], showcasing the critical role of scientific research in conservation planning.

Evaluating the impact of environmental stressors, researchers explore seeds' similarity between cultural and natural flora in southern Ukraine under chloride load [168]. Furthermore, the section highlights the importance of information provision for monitoring sustainable development [169], emphasizing the synergy between ecological research and effective management strategies.

Intricacies of marine ecosystems come to the fore as a system of environmentally important decision-making is delineated for the sustainable use of marine estuaries in the face of anthropogenic and climatic changes [170]. Chromosomal studies in Pelophylax ridibundus across different populations unveil insights into the genetic makeup of amphibian populations in southern Ukraine [171].

Expanding the horizon, researchers probe the impact of mini-hydropower on water chemistry and phytoplankton in Ukrainian reservoirs [172], offering a glimpse into the intersection of renewable energy and ecosystem dynamics. The section culminates in an analytical examination of wind farm impact on bats, using activity indices and species diversity to decipher the intricate relationship between wind energy and bat populations [173].

Through temporal dynamics of steppe plant communities [174] and differential ecomorphic analysis of urban park vegetation [175], this proceedings section encapsulates the nuanced exploration of ecological shifts and biodiversity assessments in a dynamically changing world. The contributions within this section collectively illuminate the multidimensional nature of environmental challenges and the intricate pathways towards sustainable solutions.

4.3. Innovations in energy systems and sustainable technologies

This section of the proceedings brings together a diverse array of presentations that collectively epitomize the cutting-edge innovations and research breakthroughs in energy systems and sustainable technologies. The talks featured in this section traverse the intricate landscapes of energy generation, consumption, storage, and efficiency, shedding light on the profound advancements shaping the future of the energy sector.

The journey commences with explorations into the application of on-board energy storage in electric locomotives for quarry railway transport [176], unveiling novel strategies to enhance energy efficiency in industrial transportation. Shifting focus to economic potential, researchers delve into the realm of anaerobic fermentation and green ammonia production [177], envisioning a pathway to leverage sustainable energy sources for the European energy market.

Monitoring and diagnostic systems for hydro units, coupled with smart grid technology, occupy the spotlight as researchers navigate the complexities of maintaining optimal technical conditions [178]. Electricity consumption simulation using advanced modeling techniques illuminates the intricate patterns that govern energy demand [179].

Addressing environmental challenges, atmospheric dispersion modeling under high uncertainty conditions provides critical insights into managing potential hazards [180]. Short-term electricity imbalance forecasting utilizing artificial neural networks underscores the synergy between cutting-edge computational methods and energy grid stability [181].

The proceedings then delve into a SWOT analysis of electric transport [182], unveiling opportunities for vehicle-to-grid (V2G) integration and its potential impact on power system sustainability. The crucial intersection of education and sustainability takes center stage as researchers delve into the role of high-quality education in fostering resilience in the face of energy challenges [183].

In the context of renewable energy development, investigations into the capabilities of Ukrainian higher educational establishments to meet personnel demands underscore the importance of knowledge dissemination [184]. The section progresses with research focused on components for heat storage materials, embracing energy storage as a cornerstone of sustainable systems [185].

From computational challenges [186–193] to real-world implementation [194–197], this proceedings section encapsulates the evolving landscape of energy systems and sustainable technologies. The presentations within this section collectively illuminate the innovative spirit driving the transition toward cleaner, more efficient, and resilient energy solutions [198].

4.4. Advancements in mining and minerals engineering

This section of the proceedings provides an insightful journey through the domain of mining and minerals engineering, where an array of research endeavors converges to advance innovation, efficiency, and sustainability within the industry. The talks featured herein encompass a diverse spectrum of subjects, ranging from pioneering technologies for mining operations to strategies optimizing resource utilization and elevating worker safety.

- *Exploring mining operations.* The section commences with an exploration of advanced control strategies applied to multi-pump systems in underground mines. This research showcases the integration of fuzzy inference systems for controlling power consumption [199]. A subsequent dive into the dynamic interplay between solid particles and hydraulic classifiers enriches our comprehension of material flow behavior [200].
- *Innovations in mining technology.* Advancements in mining technology take center stage, introducing innovative approaches to equipment combinations within longwall mining. These adaptations exemplify the industry's resourceful response to geological challenges [201]. Concurrently, the utilization of vibratory jaw crushers with inclined crushing chambers symbolizes the pursuit of processing efficiency for brittle materials [202].
- *Balancing economics and sustainability.* The conference also delves into economic dimensions, investigating the intricate nexus between open pit productivity and wider economic indicators of mining development [203, 204]. Furthermore, a meticulous study of hydroerosion process parameters provides pivotal insights for sustainable mining practices [205].
- *Resource optimization and development.* Optimization emerges as a central theme, from determining drilling parameters to enhance resource extraction efficiency [206]. Meanwhile, the proceedings encompass sustainable development initiatives, such as cluster creation and risk management strategies that enhance worker safety [207].
- *Maximizing efficiency in mining processes.* In-depth insights into the operation of percussion downhole drilling machines reflect the industry's commitment to process optimization [208], yielding pathways to enhanced productivity. Investigating the component composition of processed forming mixtures underscores the need for resource reuse through mineralogical analysis and reuse recommendations [209].
- *Strategic approaches to sustainability.* Sustainability takes a prominent role through discussions on sustainable development approaches via mining cluster creation [210], highlighting collaborative clusters as drivers of regional growth while adhering to sustainability principles. A study centered on clusterization of dissipative structures enhances our understanding of complex systems' behavior [211].
- *Predictive models for safer mining.* Numerical simulation of surface subsidence during coal seam excavation advances predictive modeling [212], enhancing safety in underground

mining operations [213]. The symposium's focus also extends to the dynamic interplay between thin-walled reinforced concrete shells and foundation soil, emphasizing structural integrity and longevity [214].

- *Resource management and analysis.* The proceedings spotlight technological solutions for efficient resource management through investigations into automatic control devices for oil quantity and quality in reservoirs [215, 216]. Integrated research into stress-strain state anomalies offers insights into subsurface behavior, guiding strategies for safer and sustainable mining practices [217].
- *Understanding raw materials.* The multifaceted nature of resource extraction is explored through inquiries into the influence of natural mineral impurities and moisture on hazardous coal seam properties [218]. Understanding raw material characteristics emerges as a cornerstone for safe and sustainable mining practices.
- *Efficiency in ore extraction.* Enhancements in caved ore drawing techniques from ore deposit footwalls exemplify the industry's commitment to economic and environmental advancement [219], contributing to more efficient ore extraction.
- *Precision in mining operations.* Identification of resistance torque in drill rod rotation underscores precision and safety in mining operations, emphasizing the importance of machinery dynamics [220].
- *Strategic resource management.* Geometrization of Kryvbas iron ore deposits leverages technology and geological analysis to inform resource management [221], illuminating the spatial dimensions of mineral deposits.
- *Enhancing mineral processing.* Refining beneficiation techniques takes center stage through parameters evaluation in the process of solid-phase pulp sedimentation [222], contributing to resource efficiency and waste reduction in mineral processing.
- *Analytical advancements.* Recognition of mineralogical and technological varieties through ultrasound backscatter spectrograms signifies progress in analytical methods, aligning with the industry's pursuit of precise and sustainable resource characterization [223].
- *Predictive models for safer operations.* The section culminates with a spotlight on resource utilization, as researchers present innovative approaches for repurposing mining waste and acid mine drainage into valuable nanoparticles [224]. Additionally, the symposium delves into the influence of mineral content and moisture on coal seam behavior, unveiling the intricate facets that underlie hazardous properties [225].

In essence, this proceedings section underscores the pivotal role of engineering and scientific advancements in shaping the future of mining and minerals engineering. Collectively, the presentations reflect the industry's unwavering pursuit of technological progress and sustainable practices, resulting in a comprehensive exploration of mining's evolving landscape.

4.5. Innovations in architecture, urban planning, and sustainability

Within the bounds of this proceedings section, a tapestry of innovative concepts and solutions in architecture, urban planning, and sustainability unfurls. The diverse array of talks curated in this section showcases the dynamic evolution of design and planning practices, rooted in both tradition and cutting-edge technology.

The exploration begins with a study on the determination of bearing capacity in biaxially bended beams, an endeavor central to structural design [226]. Bridging the gap between the built environment and nature, a biotechnical approach to enhance indoor and outdoor air quality captures the essence of sustainability in architecture [227].

The integration of information systems takes center stage as a multi-stage analysis of object models on construction sites is presented [228]. This discourse transcends conventional boundaries, reflecting the synergistic blend of technology and construction practices.

Groundwater treatment using polystyrene foam filters exemplifies the innovative application of materials in environmental engineering [229]. This approach showcases the ingenious ways in which modern materials can contribute to ecological solutions.

History and culture intertwine as traditional settlements are explored for lessons in preservation. Comparative studies of Shirakawa village in Japan and Kryvorivnia village in Ukraine delve into strategies for preserving heritage while maintaining functionality [230].

In post-conflict landscapes [231], the principles of urban restoration are examined, offering insights into the intricate balance of reconstructing urban spaces that are both functional and reflective of the community's needs [232].

The section concludes with an insightful overview of transformational processes in sustainable urban development, specifically in the context of Ukraine [233]. Perspectives on cultural tourism's development in the Carpathian region lend depth to the discourse [234], reflecting the intersection of cultural heritage and economic growth.

As a blend of innovative thinking, traditional wisdom, and contemporary technological advancements, this section encapsulates the essence of architecture, urban planning, and sustainability. The talks therein serve as a testament to the multifaceted nature of these disciplines and their profound impact on shaping the present and future of our built environment.

4.6. Advances in hydrology, water management, and environmental engineering

This section of the proceedings unearths a diverse range of talks, each a vital piece in the mosaic of hydrology, water management, and environmental engineering [235]. The common thread woven through these discussions is a shared commitment to preserving, managing, and optimizing one of our planet's most precious resources – water.

The journey commences with the exploration of the hydrological regime of the Uzh River under the complex interplay of backwater conditions [236]. In striving to mitigate risks in urban environments, this study probes the intricate dynamics of river systems and their interaction with urban landscapes.

Advancements in technology are showcased in the realm of water regulation and drainage. The evolution of modular systems within the humid zone's landscapes underscores the innovative potential to manage and control water flow in dynamic environments [237].

The quantitative assessment of water quality in the "Vidsichne" reservoir serves as a cornerstone of environmental stewardship. By delving into the intricate chemistry and biology of water bodies, this research [238] lays the foundation for informed decision-making in water resource management.

In the context of the digital age, a forward-looking perspective emerges. The role of Ukraine in the global trends of sustainable development is critically analyzed within the framework of the digital economy [239], reflecting the intricate interplay between technology and sustainability.

The biological treatment of wastewater is dissected as the phenomenon of bulking in activated sludge systems is scrutinized. Through this lens, the symbiotic relationship between microbiology and environmental engineering comes to light [240], with implications for sustainable wastewater treatment.

The section delves into the hydrogeological and ameliorative state of the Kilchen irrigation system territory, a testament to the multidisciplinary nature of environmental engineering. This study [241] echoes the broader imperative of harmonizing human activities with the natural environment.

From biomass to gases, sustainable processing takes center stage as the extraction of pollutants from flue gases through mechanical activation is investigated [242]. This speaks to the confluence of chemical engineering, environmental science, and sustainability goals.

Rounding out the section is a methodological exploration, a blueprint for determining the availability of natural moistening for land reclamation needs. This research [243] underscores the intricate nexus of climate, hydrology, and land management.

In essence, this section reflects the interdisciplinary nature of hydrology, water management, and environmental engineering. It underscores the relentless pursuit of sustainable solutions in an ever-changing world, where the preservation of water resources and the environment stand as pivotal endeavors.

4.7. Ecology, renewable energy, and resource management

Within the tapestry of these proceedings lies a section dedicated to exploring the delicate balance between ecology, renewable energy, and resource management. The talks within this segment delve into the intricate dance between humanity and its environment, seeking sustainable harmony.

The Southern Bug River mouth ecosystem is unveiled in all its complexity, offering a snapshot of its current state [244]. Through meticulous study, the intricate web of interactions that sustains this ecosystem comes into focus, revealing insights into the challenges and opportunities for conservation and restoration.

Shifting gears, the energy dynamics of solar panels and inverters intertwine with the broader electric network. This study [245] scrutinizes the marriage of renewable energy and grid infrastructure, offering glimpses into the optimization and challenges of harnessing sunlight to power our lives.

In the world of fisheries, probiotic microorganisms find a place in the production technology of European grayling fish stock [246]. The intersection of biology and aquaculture is explored, illustrating how microorganisms can contribute to the well-being of aquatic ecosystems and sustainable fish farming.

Heap leaching emerges as a technique for extracting gold from oxidized ore, with the Belsu deposit as its backdrop [247]. This method, rooted in chemical engineering, showcases how modern technologies can unlock the value of mineral resources while minimizing environmental impact.

A focus on spatial development drives a quest to enhance indicators that illuminate the transformation of territories. Through thoughtful analysis, this research [248] offers insights into urban planning, land use, and the intricate relationships that shape the built environment.

In the heart of the Ukrainian Carpathians, the potential of biomass from forest residues takes center stage [249]. This exploration of regional green economy emphasizes the symbiotic relationship between sustainable forestry practices, economic growth, and environmental stewardship.

The section also delves into cadastral and landscape modeling of lakes, casting light on the role of proper resource management in sustaining natural beauty and recreational opportunities [250]. This approach demonstrates the synergy between ecological conservation and human enjoyment.

Lastly, the interplay between social and environmental features becomes apparent through an examination of minerals resources classification systems [251]. Intrinsic connections are forged between societal needs, resource extraction, and environmental protection, reflecting the complexity of resource management.

This section encapsulates the intricate tapestry of humanity's relationship with its surroundings. It shines a light on the sustainable pathways forward, where ecology, renewable energy, and resource management converge to shape a harmonious future.

4.8. Environmental science and sustainability

The section consists of 21 talks that address various environmental issues and solutions in the context of war and energy. The talks are grouped into four sub-sections: radiation pollution, energy production, environmental risk assessment, and ecological diversity.

The first sub-section focuses on radiation pollution caused by war and nuclear power plants. The talks in this sub-section present mathematical tools for restoring the surface distribution of radiation pollution based on remote measurement data [252, 253], a conceptual scheme for creating environmentally friendly Gd-containing neutron-absorbing nanocomposites [254], a factor-criterion model for selecting the optimal option for transforming the "Shelter" object into an environmentally safe system [255], and the formation of the carbonate system of circulating cooling water of the Rivne NPP and its influence on the surface waters pH levels of the Styr River [256]. These talks provide novel approaches and techniques for reducing the radiation exposure and contamination of humans and the environment.

The second sub-section focuses on energy production from various sources, such as nuclear, biogas, and nanocomposites. The talks in this sub-section present a neural network model of investment process of biogas production [257], perspectives of nuclear energy development in Ukraine on the global trends basis [258], and development of recommendations for improving the radiation monitoring system of Ukraine. These talks explore the feasibility, benefits, and challenges of different energy options for meeting the growing energy demand and reducing greenhouse gas emissions.

The third sub-section focuses on environmental risk assessment of water bodies [259, 260], soil [261], air [262], and natural ecosystems in the conditions of mineral deposits development, warfare [263], transportation of dangerous substances [264], and fuel and energy complex [265]. The talks in this sub-section present methods and tools for assessing environmental risk using mathematical models, innovative technologies [266], scientific and methodological approaches, decision-making support tools, environmental biomonitoring, satellite imagery [267], etc. These talks aim to identify, quantify, and manage the environmental hazards and impacts of various human activities.

The fourth sub-section focuses on ecological diversity of different organisms in response to environmental stressors, such as electromagnetic pollution, pesticides, urbanization, etc. The talks in this sub-section present studies on the impact of electromagnetic pollution on the phytocenotic diversity of the transcordon region [268], the coherence of the formation of containing and ore containing Precambrian formations Orikhovo-Pavlograd suture zone of the Ukrainian shield [269], ecological adaptations among spruce species along an environmental gradient in urban areas [270], impact of pesticides on the respiration of Planorbarius (superspecies) corneus s. l. allospecies from the Ukrainian river network [271], environmental safety of soil genetic horizons in the impact zone of Lviv city landfill [272], etc. These talks reveal the effects of environmental stressors on the structure, function, and evolution of different biological systems.

The section offers a comprehensive overview of the current state-of-the-art research on environmental challenges and solutions in the context of war and energy. The section also highlights the gaps and directions for future research in this field. The section is relevant and timely for researchers, practitioners, policy makers, and general public who are interested in or concerned about the environmental issues facing Ukraine and other regions.

4.9. Economic and business sustainability

Encompassing a diverse array of talks, this section delves into the intricate interplay between economic practices, business strategies, and sustainable development [273], illuminating pathways toward a sustainable future.

The transformation of Ukraine's national financial system emerges as a pivotal discussion.

Through the lens of sustainability, this exploration [274] unravel novel strategies for integration, aligning economic structures with the principles of environmental and social equilibrium.

The concept of social responsibility takes center stage as its integration within business practices is examined. This inquiry [275] underscores the evolving role of corporations in driving sustainable development, reflecting a growing recognition of the interdependence between business success and societal well-being.

The section delves into the realm of forestry enterprises, dissecting their potential management for sustainable outcomes. By scrutinizing the efficiency of forestry practices, this study [276] offer insights into the conservation of vital natural resources.

The grain industry's investment and operational costs are harmonized through the lens of sustainable development theory. This paper [277] illuminate the complex dance between economic profitability and environmental stewardship within the agricultural domain.

A model-driven exploration into socio-economic systems' sustainable development processes enriches the section. By employing analytical tools, this study [278] unravel the intricate dynamics underpinning societal progress and resilience.

The creation of a favorable environment for organic production emerges as a critical precursor to agricultural sustainability. The study [279] within this section underline how policy instruments can shape agricultural practices to align with ecological and social well-being.

The multi-dimensional nature of Ukraine's sustainable development is meticulously dissected through a structural econometric lens. This study [280] paint a comprehensive picture of the nation's progress, considering its social, economic, and environmental facets.

Addressing the evolving landscape of investment, the assessment of ESG (Environmental, Social, and Governance) competitiveness takes center stage. The study [281] illuminate how enterprises can navigate the shifting expectations of new-generation investors, aligning financial success with sustainable principles.

The post-COVID-19 economic recovery process comes under scrutiny through the lens of Sustainable Development Goals (SDGs). This reseatch [282] navigate the dual challenge of economic rejuvenation while upholding the principles of sustainability.

The section concludes with a focus on the Black Sea Region's role in the global grain trade and the challenges that underpin its development [283]. The economic implications of regional trade dynamics offer insights into the complex balance between trade, sustainability, and economic growth.

As a collective, this section unveils a mosaic of economic and business strategies, each thread intricately woven into the fabric of sustainable development. These studies underscore that economic prosperity can indeed coexist harmoniously with environmental and social well-being.

4.10. Geospatial and technological applications for sustainability

This section delves into the realm of geospatial technology and innovative applications that hold the key to sustainable development in diverse domains. These talks navigate the convergence of technology and sustainability, offering insights into the transformative potential of cutting-edge solutions.

The development of a predictive and search system for amber stands as a testament to the fusion of technology with resource management. By harnessing advanced algorithms, this study [284] seek to optimize the exploration of precious resources while aligning with sustainable practices.

Exploring land use policy implementation at the local level, this section demystifies the conceptual and terminological intricacies. By elucidating the policy landscape, this study [285] contribute to the formulation of strategies that foster sustainable land management practices.

Mining tourism emerges as a catalyst for sustainable development, especially in industrial regions like Kryvyi Rih. This study [286] showcase how the fusion of heritage, industry, and responsible tourism can pave the way for socio-economic progress while preserving local identities.

The integration of remote sensing in assessing military destruction and its aftermath in Ukraine opens new frontiers for data-driven analysis. The study [287] employ technology to unravel the consequences of conflict, spotlighting the interplay between security, resilience, and recovery.

Switching gears, the section delves into the characteristics of BlaBlaCar, a ridesharing giant that exemplifies a sustainable transport solution. This study [288] unravel the potential of the sharing economy to reshape urban mobility and mitigate environmental impacts.

Addressing the rational use of mineral resources and mining waste, this section highlights the symbiotic relationship between industry and environmental sustainability. The study [289] delve into innovative practices that minimize waste while optimizing resource utilization.

Technological innovation takes center stage with investigations into an energy-efficient screw oil press. By reimagining traditional processes, the study [290] underscore how technology can drive efficiency gains with far-reaching ecological implications.

The integration of GIS technologies for geodetic monitoring resonates with this section's overarching theme [291]. This study [292] unveil how geospatial tools offer real-time insights, shaping effective decision-making processes across diverse domains.

Geographical foundations of the sustainable development concept are examined from a paradigmatic level. This study [293] contextualize sustainable development within the fabric of geographic principles, unearthing the interconnectedness of space, environment, and human progress.

Optimized fuel values are scrutinized as a strategy for emission reduction. This study [294] explore the potential of fuel optimization to mitigate environmental impacts, showcasing how technology can revolutionize conventional energy practices.

Engineering analysis of transverse loading dynamics in rail transportation underlines the integration of technology into logistical processes. These studies [295, 296] uncover insights into load-bearing dynamics, with implications for efficient and sustainable transportation.

Energy potential within high-altitude mining transport systems receives attention in this section. These explorations [297] unveil the latent energy resources within mining operations, offering novel strategies for sustainability in challenging environments.

The section culminates in a deep dive into pathophysiological mechanisms, unraveling how technology intersects with health science. These inquiries probe the physiological adaptation of gastric cardia mucosa underlining how scientific understanding can inform sustainable healthcare practices [298].

5. Conclusion

The vision driving ICSF 2023 is to establish a paramount interdisciplinary platform, uniting researchers, practitioners, and educators, to showcase and deliberate upon the latest innovations, emerging trends, concerns, practical challenges, and adopted solutions in the realm of sustainability.

We extend our sincere gratitude to the authors who submitted their papers and to the delegates for their enthusiastic participation and interest in ICSF as a conduit for sharing ideas and innovation. Our heartfelt appreciation also extends to the program committee members, whose unwavering guidance, dedication, and the invaluable contributions of peer reviewers have elevated the quality of the papers. The constructive critiques, improvements, and corrections they provided have significantly enriched the success of this conference. We also recognize the pivotal role of Morressier's developers, whose robust conference management system facilitated every stage of the process, from soliciting papers to coordinating peer reviews and crafting the conference proceedings volume.

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As we move forward, we anticipate exceptional presentations and insightful discussions that will expand our professional horizons. We hope that all participants find immense value in this conference and eagerly anticipate the prospect of reconnecting in a more convivial, light-hearted, and harmonious setting at ICSF 2024. The next installment in the series, the 5th International Conference on Sustainable Futures: Environmental, Technological, Social, and Economic Matters, is set to take place in May 2024 in Kryvyi Rih, Ukraine (https://icsf.ccjournals.eu/2024/).

Thank you all for being an integral part of ICSF 2023, and here's to a brighter, more sustainable future that we collectively strive to build.

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References

[1] Semerikov S, Chukharev S, Sakhno S, Striuk A, Osadchyi V, Solovieva V, Vakaliuk T, Nechypurenko P, Bondarenko O and Danylchuk H 2020 *E3S Web of Conferences* **166** 00001 ISSN 25550403 URL https://doi.org/10.1051/e3sconf/202016600001

[2] Semerikov S, Chukharev S, Sakhno S, Striuk A, Iatsyshyn A, Klimov S, Osadchyi V, Vakaliuk T, Nechypurenko P, Bondarenko O and Danylchuk H 2021 *E3S Web of Conferences* **280** 00001 URL https://doi.org/10.1051/e3sconf/202128000001

[3] Semerikov S O, Chukharev S M, Sakhno S I, Striuk A M, Iatsyshin A V, Klimov S V, Osadchyi V V, Vakaliuk T A, Nechypurenko P P, Bondarenko O V and Danylchuk H B 2022 *IOP Conference Series: Earth and Environmental Science* **1049**(1) 011001 URL https://doi.org/10.1088/1755-1315/1049/1/011001

[4] Semerikov S O, Chukharev S M, Sakhno S I, Striuk A M, Iatsyshin A V, Klimov S V, Osadchyi V V, Vakaliuk T A, Nechypurenko P P, Bondarenko O V, Danylchuk H B and Artemchuk V O 2023 4th International Conference on Sustainable Futures: Environmental, Technological, Social and Economic Matters *IOP Conference Series: Earth and Environmental Science*

[5] Abdillah L A, Sari I N and Indriani D E 2018 *International Journal of Engineering and Technology(UAE)* **7**(3) 1463 – 1467

[6] Yusupov K A, Rysbekov K B, Aben K K and Bakhmagambetova G B 2021 *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu* **2021**(3) 14 – 18 URL https://doi.org/10.33271/nvngu/2021-3/014

[7] Abuselidze G 2018 *Journal of Applied Economic Sciences* **13**(7) 1929 – 1938

[8] Sinha A, Nikhil S, Ajin R S, Danumah J H, Saha S, Costache R, Rajaneesh A, Sajinkumar K S, Amrutha K, Johny A, Marzook F, Mammen P C, Abdelrahman K, Fnais M S and Abioui M 2023 *Fire* **6**(2) URL https://doi.org/10.3390/fire6020044

[9] Alpatova O M, Garlinska A M and Bordyug N S 2019 *Hydrobiological Journal* **55**(1) 36–43 ISSN 0018-8166 URL https://www.dl.begellhouse.com/journals/38cb2223012b73f2,51cfce8a0ce6f810,76e641502b94854f.html

[10] Phang F A, Pusppanathan J, Nawi N D, Zulkifli N A, Zulkapri I, Harun F K C, Khang A W Y, Alsayaydeh J A J and Sek T K 2021 *International Journal of Emerging Technologies in Learning* **16**(15) 78 – 90 URL https://doi.org/10.3991/ijet.v16i15.23673

[11] Gurieiev V, Kutsan Y, Iatsyshyn A, Iatsyshyn A, Kovach V, Lysenko E, Artemchuk V and Popov O 2020 Simulating Systems for Advanced Training and Professional Development of Energy Specialists in Power Sector *Proceedings of the 16th International Conference on ICT in Education, Research and Industrial Applications. Integration, Harmonization and Knowledge Transfer. Volume II: Workshops, Kharkiv, Ukraine, October 06-10, 2020* (*CEUR Workshop Proceedings* vol 2732) ed Sokolov O, Zholtkevych G, Yakovyna V, Tarasich Y, Kharchenko V, Kobets V, Burov O, Semerikov S and Kravtsov H (CEUR-WS.org) pp 693–708 URL https://ceur-ws.org/Vol-2732/20200693.pdf

[12] Babenko V, Chebanova N, Ryzhikova N, Rudenko S and Birchenko N 2018 *Eastern-European Journal of Enterprise Technologies* **1**(3-91) 4 – 12 URL https://doi.org/10.15587/1729-4061.2018.123461

[13] Bendík J, Cenký M, Cintula B, Beláň A, Eleschová v and Janiga P 2023 *Processes* **11**(1) URL https://doi.org/10.3390/pr11010009

[14] Makarov V, Kaplin M, Bilan T and Perov M 2021 Modeling the Coal Industry Technological Development Considering Environmental Restrictions *Systems, Decision and Control in Energy II* ed Zaporozhets A and Artemchuk V (Cham: Springer International Publishing) pp 153–165 ISBN 978-3-030-69189-9 URL https://doi.org/10.1007/978-3-030-69189-9_9

[15] Blinov I V and Parus Y V 2015 *Technical Electrodynamics* **2015**(4) 81 – 88

[16] Neelgund G M, Bliznyuk V N, Pud A A, Fatyeyeva K Y, Hrehorova E and Joyce M 2010 *Polymer* **51**(9) 2000–2006 ISSN 0032-3861 URL https://doi.org/10.1016/j.polymer.2010.02.038

[17] Kholoshyn I, Nazarenko T, Bondarenko O, Hanchuk O and Varfolomyeyeva I 2021 *Journal of Physics: Conference Series* **1840**(1) 012017 URL https://doi.org/10.1088/1742-6596/1840/1/012017

[18] Moskalets V, Knyazyuk O, Bordiug N, Ishchuk O and Matkovska S 2023 *Scientific Horizons* **26**(6) 43 – 57 URL https://doi.org/10.48077/scihor6.2023.43

[19] Orkhontuul B 2007 Analysis of truck dismounting process *2007 International Forum on Strategic Technology* pp 457–458 URL https://doi.org/10.1109/IFOST.2007.4798630

[20] Kholoshyn I V, Mantulenko S V, Burman L V, Joyce A S and Sherick D 2022 *IOP Conference Series: Earth and Environmental Science* **1049**(1) 012075 URL https://doi.org/10.1088/1755-1315/1049/1/012075

[21] Bendík J, Cenký M, Eleschová Ž, Beláň A, Cintula B and Janiga P 2022 Stochastic Concept for Modeling Distributed Energy Resources in Power Systems *2022 22nd International Scientific Conference on Electric Power Engineering (EPE)* pp 1–6 URL https://doi.org/10.1109/EPE54603.2022.9814093

[22] Panayotov V, Panayotova M and Chukharev S 2020 *E3S Web of Conferences* **166** 06012 URL https://doi.org/10.1051/e3sconf/202016606012

[23] Kiv A E, Soloviev V N, Semerikov S O, Danylchuk H B, Kibalnyk L O, Matviychuk A V and Striuk A M 2021 Machine learning for prediction of emergent economy dynamics III *Proceedings of the Selected and Revised Papers of 9th International Conference on Monitoring, Modeling & Management of Emergent Economy (M3E2-MLPEED 2021), Odessa, Ukraine, May 26-28, 2021* (*CEUR Workshop Proceedings* vol 3048) ed Kiv A E, Soloviev V N and Semerikov S O (CEUR-WS.org) pp i–xxxi URL https://ceur-ws.org/Vol-3048/paper00.pdf

[24] Krasnov V P, Orlov O O, Zborovska O V, Zhukovsky O V, Kurbet T V, Shelest Z M and Davydova I V 2018 *Nuclear Physics and Atomic Energy* **19**(4) 383 – 391 URL https://doi.org/10.15407/jnpae2018.04.383

[25] Kuzev L, Kostadinov E, Damyanov T, Dedelyanova K and Hristov N 2014 Comperative experimental study of two grinding media *IMPC 2014 - 27th International Mineral Processing Congress*

[26] Anistratenko V V, Furyk Y I, Degtyarenko E V and Anistratenko O Y 2017 *Ecologica Montenegrina* **13** 70 – 79

[27] Demchenko V A and Demchenko N A 2015 *Russian Journal of Biological Invasions* **6**(2) 78–86 ISSN 2075-1125 URL https://doi.org/10.1134/S2075111715020022

[28] Chernichko J I, Demchenko V A, Podorozhny S N, Zhmud M Y and Suchkov S I 2022 *IOP Conference Series: Earth and Environmental Science* **1049**(1) 012065 URL https://doi.org/10.1088/1755-1315/1049/1/012065

[29] Denisenko V S and Slyn'ko V I 2015 *Journal of Computer and Systems Sciences International* **54**(1) 1–12

ISSN 1555-6530 URL https://doi.org/10.1134/S1064230714050050
[30] Sadovenko I O, Zahrytsenko A M, Podvihina O O and Dereviahina N I 2017 *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu* 19 – 26
[31] Derkach T M 2019 *Orbital* **11**(3) 219 – 227 URL https://doi.org/10.17807/orbital.v11i3.1395
[32] Dmytrenko V I, Zezekalo I G and Vynnykov Y L 2022 *IOP Conference Series: Earth and Environmental Science* **1049**(1) 012052 URL https://doi.org/10.1088/1755-1315/1049/1/012052
[33] Dubovkina I, Sigal O, Rikhter V and Nizhnyk N 2021 *Ukrainian Food Journal* **10**(4) 828 – 839 URL https://doi.org/10.24263/2304-974X-2021-10-4-15
[34] Yeremeyev I, Dychko A, Kyselov V, Remez N, Kraychuk S and Ostapchuk N 3919 *Latvian Journal of Physics and Technical Sciences* **56**(4) 57–67 URL https://doi.org/10.2478/lpts-2019-0025
[35] Filatiev M 2017 *Mining of Mineral Deposits* **11**(2) 91 – 95 URL https://doi.org/10.15407/mining11.02.091
[36] Jovanovic S, Gligoric Z, Beljic C, Gluscevic B and Cvijovic C 2014 *Arabian Journal for Science and Engineering* **39**(6) 4529–4539 ISSN 2191-4281 URL https://doi.org/10.1007/s13369-014-1173-9
[37] Grinchenko V S 2018 *Technical Electrodynamics* **2018** 29 – 32 URL https://doi.org/10.15407/techned2018.04.029
[38] Pihulevskyi P G, Anisimova L B, Kalinichenko O O, Panteleeva N B and Hanchuk O V 2021 *Journal of Physics: Conference Series* **1840**(1) 012018 URL https://doi.org/10.1088/1742-6596/1840/1/012018
[39] Korobiichuk I, Davydova I, Korobiichuk V, Shlapak V and Herasymchuk O 2020 The Influence of Geological and Anthropogenic Factors on the Change of the Water Quality Parameters in the Kamyanka River Within the City of Zhytomyr *Mechatronics 2019: Recent Advances Towards Industry 4.0* ed Szewczyk R, Krejsa J, Nowicki M and Ostaszewska-Liżewska A (Cham: Springer International Publishing) pp 476–486 ISBN 978-3-030-29993-4 URL https://doi.org/10.1007/978-3-030-29993-4_59
[40] Mokhor V, Korchenko O, Honchar S, Komarov M and Onyskova A 2021 *E3S Web of Conferences* **280** 09009 URL https://doi.org/10.1051/e3sconf/202128009009
[41] Hristova T, Gabrovska-Evstatieva K and Evstatiev B 2021 *Journal of E-Learning and Knowledge Society* **17**(1) 62 – 71 URL https://doi.org/10.20368/1971-8829/1135420
[42] Hryhoruk P, Khrushch N and Grygoruk S 2020 Assessing the Investment Capacity of the Agricultural Sector: Case of Ukraine *2020 10th International Conference on Advanced Computer Information Technologies (ACIT)* pp 183–187 URL https://doi.org/10.1109/ACIT49673.2020.9208927
[43] Zinovieva I S, Artemchuk V O, Iatsyshyn A V, Romanenko Y O, Popov O O, Kovach V O, Taraduda D V and Iatsyshyn A V 2021 *Journal of Physics: Conference Series* **1946**(1) 012011 URL https://doi.org/10.1088/1742-6596/1946/1/012011
[44] Kovach V, Deinega I, Iatsyshyn A, Iatsyshyn A, Kovalenko V and Buriachok V 2019 Electronic Social Networks as Supporting Means of Educational Process in Higher Education Institutions *Proceedings of the International Workshop on Conflict Management in Global Information Networks (CMiGIN 2019) co-located with 1st International Conference on Cyber Hygiene and Conflict Management in Global Information Networks (CyberConf 2019), Lviv, Ukraine, November 29, 2019* (*CEUR Workshop Proceedings* vol 2588) ed Fedushko S, Gnatyuk S, Peleshchyshyn A, Hu Z, Odarchenko R and Korobiichuk I (CEUR-WS.org) pp 418–433 URL https://ceur-ws.org/Vol-2588/paper35.pdf
[45] Buratynskyi I, Nechaieva T, Shulzhenko S and Ivanenko N 2021 The Optimization of PV-plant's DC/AC Equipment Ratio Using the Non-linear Least-cost Model *2021 IEEE 3rd Ukraine Conference on Electrical and Computer Engineering (UKRCON)* pp 358–362 URL https://doi.org/10.1109/UKRCON53503.2021.9575720
[46] Zverkovskyy V M, Sytnyk S A, Lovynska V M, Kharytonov M M, Lakyda I P, Mykolenko S Y, Pardini G, Margui E and Gispert M 3918 *Ekológia (Bratislava)* **37** 69–81 URL https://doi.org/10.2478/eko-2018-0007
[47] Klimov S V and Klimova A V 2022 *IOP Conference Series: Earth and Environmental Science* **1049**(1) 012038 URL https://doi.org/10.1088/1755-1315/1049/1/012038
[48] Kukharenko V N, Fedosova A P, Kolgatin A G and Dosov V G 1992 *Khimicheskoe I Neftegazovoe Mashinostroenie* (5) 19 – 21
[49] Komarova E V 2021 *Journal of Physics: Conference Series* **1840**(1) 012010 URL https://doi.org/10.1088/1742-6596/1840/1/012010
[50] Malanchuk Z, Korniyenko V, Malanchuk Y, Khrystyuk A and Kozyar M 2020 *E3S Web of Conferences* **166** 02008 URL https://doi.org/10.1051/e3sconf/202016602008
[51] Lysychenko G, Weber R, Kovach V, Gertsiuk M, Watson A and Krasnova I 2015 *Environmental Science and Pollution Research* **22**(19) 14391–14404 ISSN 1614-7499 URL https://doi.org/10.1007/s11356-015-5184-1
[52] Bessalov A V and Kovalchuk L V 2019 *Cybernetics and Systems Analysis* **55**(5) 731–741 ISSN 1573-8337

URL https://doi.org/10.1007/s10559-019-00183-y

[53] Danylchuk H, Ivanylova O, Kibalnyk L, Kovtun O, Melnyk T, Serdiuk O and Zaselskiy V 2020 Modelling of trade relations between EU countries by the method of minimum spanning trees using different measures of similarity *Proceedings of the Selected Papers of the Special Edition of International Conference on Monitoring, Modeling & Management of Emergent Economy (M3E2-MLPEED 2020), Odessa, Ukraine, July 13-18, 2020* (*CEUR Workshop Proceedings* vol 2713) ed Kiv A (CEUR-WS.org) pp 167–186 URL https://ceur-ws.org/Vol-2713/paper13.pdf

[54] Kuchanskyy V 2017 The application of controlled switching device for prevention resonance overvoltages in nonsinusoidal modes *2017 IEEE 37th International Conference on Electronics and Nanotechnology (ELNANO)* pp 394–399 URL https://doi.org/10.1109/ELNANO.2017.7939785

[55] Zadiraka V K and Kudin A M 2017 *Cybernetics and Systems Analysis* **53** 978–985 ISSN 1573-8337 URL https://doi.org/10.1007/s10559-017-9999-2

[56] Sinchuk O, Kupin A, Sinchuk I, Rohoza M and Plieshkov P 2020 *Mining of Mineral Deposits* **14**(3) 101 – 111 URL https://doi.org/10.33271/mining14.03.101

[57] Smyrnova-Trybulska E, Morze N, Kuzminska O and Kommers P 2018 *Journal of Information, Communication and Ethics in Society* **16**(4) 381 – 400 URL https://doi.org/10.1108/JICES-03-2018-0028

[58] Pysmennyi S, Chukharev S, Khavalbolot K, Bondar I and Ijilmaa J 2021 *E3S Web of Conferences* **280** 08013 URL https://doi.org/10.1051/e3sconf/202128008013

[59] Lavrov E and Pasko N 2018 *CEUR Workshop Proceedings* **2105** 445 – 448

[60] Lazăr M, Faur F G, Dunca E and Ciolea D I 2017 *Environmental Engineering and Management Journal* **16**(6) 1301 – 1308 URL https://doi.org/10.30638/eemj.2017.138

[61] Levkivskyi V, Lobanchykova N and Marchuk D 2020 *E3S Web of Conferences* **166** 05007 URL https://doi.org/10.1051/e3sconf/202016605007

[62] Olytsky O, Yermakov V, Lunova O and Buglak O 2019 *Space Science and Technology* **25**(4) 48 – 56 URL https://doi.org/10.15407/knit2019.04.048

[63] Ivanov M, Maksyshko N, Ivanov S M and Terentieva N 2020 Intelligent data analysis in hr process management *Proceedings of The Third International Workshop on Computer Modeling and Intelligent Systems (CMIS-2020), Zaporizhzhia, Ukraine, April 27-May 1, 2020* (*CEUR Workshop Proceedings* vol 2608) ed Subbotin S (CEUR-WS.org) pp 754–768 URL https://ceur-ws.org/Vol-2608/paper57.pdf

[64] Malchenko S L, Tsarynnyk M S, Poliarenko V S, Berezovska-Savchuk N A and Liu S 2021 *Journal of Physics: Conference Series* **1946**(1) 012010 URL https://doi.org/10.1088/1742-6596/1946/1/012010

[65] Lezhnjuk P D, Kulik V V, Burykin O B, Malogulko J V, Kacejko P and Abenov A 2018 Transmission loss allocation for a bilateral contract in deregulated electricity market *Photonics Applications in Astronomy, Communications, Industry, and High-Energy Physics Experiments 2018* vol 10808 ed Romaniuk R S and Linczuk M International Society for Optics and Photonics (SPIE) p 1080865 URL https://doi.org/10.1117/12.2501604

[66] Matsui A 2015 *Metallurgical and Mining Industry* **7**(1) 18 – 21

[67] Souas F and Meddour A S E 2022 *Journal of Pipeline Science and Engineering* **2**(4) 100088 ISSN 2667-1433 URL https://doi.org/10.1016/j.jpse.2022.100088

[68] Tovarovskii I G and Merkulov A E 2016 *Metallurgist* **60**(5) 589–593 ISSN 1573-8892 URL https://doi.org/10.1007/s11015-016-0336-1

[69] Mytiai I S, Matsyura A V, Jankowski K and Mytiai Z 2020 *Ecologica Montenegrina* **38** 67–78 URL https://doi.org/10.37828/em.2020.38.9

[70] Dura C, Păun A P and Moraru R I 2018 *Quality - Access to Success* **19**(162) 155 – 160

[71] Pysmennyi S, Chukharev S, Kyelgyenbai K, Mutambo V and Matsui A 2022 *IOP Conference Series: Earth and Environmental Science* **1049**(1) 012008 URL https://doi.org/10.1088/1755-1315/1049/1/012008

[72] Mykhailenko O and Budnikov K 2022 *IOP Conference Series: Earth and Environmental Science* **1049**(1) 012055 URL https://doi.org/10.1088/1755-1315/1049/1/012055

[73] Yarkov S V, Nazarenko T H, Panteleeva N B, Bondarenko O V and Varfolomyeyeva I M 2022 *IOP Conference Series: Earth and Environmental Science* **1049**(1) 012036 URL https://doi.org/10.1088/1755-1315/1049/1/012036

[74] Nazimko V 2018 *Acta Geodynamica et Geomaterialia* **15** 379 – 393 URL https://doi.org/10.13168/AGG.2018.0028

[75] Nechypurenko P, Evangelist O, Selivanova T and Modlo Y O 2020 Virtual Chemical Laboratories as a Tools of Supporting the Learning Research Activity of Students in Chemistry While Studying the Topic "Solutions" *Proceedings of the 16th International Conference on ICT in Education, Research and Industrial Applications. Integration, Harmonization and Knowledge Transfer. Volume II: Workshops, Kharkiv, Ukraine, October 06-10, 2020* (*CEUR Workshop Proceedings* vol 2732) ed Sokolov O, Zholtkevych G, Yakovyna V, Tarasich Y, Kharchenko V, Kobets V, Burov O, Semerikov S and Kravtsov

H (CEUR-WS.org) pp 984–995 URL https://ceur-ws.org/Vol-2732/20200984.pdf
[76] Kovalchuk L, Kaidalov D, Shevtsov O, Nastenko A, Rodinko M and Oliynykov R 2017 Analysis of splitting attacks on Bitcoin and GHOST consensus protocols *2017 9th IEEE International Conference on Intelligent Data Acquisition and Advanced Computing Systems: Technology and Applications (IDAACS)* vol 2 pp 978–982 URL https://doi.org/10.1109/IDAACS.2017.8095233
[77] Osadchyi V V, Osadcha K P, Varina H B, Shevchenko S V and Bulakh I S 2021 *Journal of Physics: Conference Series* **1946**(1) 012022 URL https://doi.org/10.1088/1742-6596/1946/1/012022
[78] Valko N V and Osadchyi V V 2021 *Journal of Physics: Conference Series* **1946**(1) 012016 URL https://doi.org/10.1088/1742-6596/1946/1/012016
[79] Bondarenko O V, Hanchuk O V, Pakhomova O V, Tsutsunashvili G and Zagórski A 2022 *IOP Conference Series: Earth and Environmental Science* **1049**(1) 012076 URL https://doi.org/10.1088/1755-1315/1049/1/012076
[80] Panayotova M 2000 *Surface and Coatings Technology* **124**(2) 266–271 ISSN 0257-8972 URL https://doi.org/10.1016/S0257-8972(99)00647-7
[81] Kholoshyn I, Burman L, Nazarenko T, Mantulenko S and Panteleeva N 2020 *E3S Web of Conferences* **166** 13007 URL https://doi.org/10.1051/e3sconf/202016613007
[82] Peremetchyk A, Kulikovska O, Shvaher N, Fedorenko S, Moraru R, Panayotov V and Chukharev S 2022 *Mining of Mineral Deposits* **16**(3) 67 – 77 URL https://doi.org/10.33271/mining16.03.067
[83] Kuzmenko O, Petlyovanyy M and Heylo A 2014 Application of fine-grained binding materials in technology of hardening backfill construction *Progressive Technologies of Coal, Coalbed Methane, and Ores Mining* p 465 – 470 URL https://doi.org/10.1201/b17547
[84] Popov O and Yatsyshyn A 2017 Mathematical Tools to Assess Soil Contamination by Deposition of Technogenic Emissions *Soil Science Working for a Living* ed Dent D and Dmytruk Y (Cham: Springer International Publishing) pp 127–137 ISBN 978-3-319-45417-7 URL https://doi.org/10.1007/978-3-319-45417-7_11
[85] Ivanov R V, Grynko T V, Porokhnya V M, Pavlov R A and Golovkova L S 2022 *IOP Conference Series: Earth and Environmental Science* **1049**(1) 012041 URL https://doi.org/10.1088/1755-1315/1049/1/012041
[86] Purskiĭ O I, Zholonko N N and Konstantinov V A 2000 *Low Temperature Physics* **26**(4) 278–281 ISSN 1063-777X URL https://doi.org/10.1063/1.593899
[87] Komliev O, Bortnyk S, Remezova O, Spytsia R, Vasylenko S and Zhylkin S 2021 The use of data on the material composition of sediments during forecasting works of titanium root and placer deposits *20th International Conference Geoinformatics: Theoretical and Applied Aspects* URL https://doi.org/10.3997/2214-4609.20215521163
[88] Sakhno I G, Molodetskyi A V and Sakhno S V 2018 *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu* (5) 48 – 53 URL https://doi.org/10.29202/nvngu/2018-5/4
[89] Sakhno S I, Yanova L O, Pischikova O V and Sergiienko T S 2022 *IOP Conference Series: Earth and Environmental Science* **1049**(1) 012050 URL https://doi.org/10.1088/1755-1315/1049/1/012050
[90] Kryvenko P V, Sanytsky M and Kropyvnytska T 2018 Alkali-sulfate activated blended portland cements *Binders, Materials and Technologies in Modern Construction IV* (*Solid State Phenomena* vol 276) (Trans Tech Publications Ltd) pp 9–14 URL https://doi.org/10.4028/www.scientific.net/SSP.276.9
[91] Zahorodko P V, Modlo Y O, Kalinichenko O O, Selivanova T V and Semerikov S O 2020 *CEUR Workshop Proceedings* **2832** 94 – 103
[92] Semerikov S O, Teplytskyi I O, Soloviev V N, Hamaniuk V A, Ponomareva N S, Kolgatin O H, Kolgatina L S, Byelyavtseva T V, Amelina S M and Tarasenko R O 2021 *Journal of Physics: Conference Series* **1840**(1) 012036 URL https://doi.org/10.1088/1742-6596/1840/1/012036
[93] Korobiichuk V, Shamrai V, Levytskyi V, Sobolevskyi R and Sydorov O 2018 *Rudarsko Geolosko Naftni Zbornik* **33**(4) 15 – 21 URL https://doi.org/10.17794/rgn.2018.4.2
[94] Tarasenko R A, Usenko S A, Shapovalov Y B, Shapovalov V B, Paschke A and Savchenko I M 2021 Ontology-based learning environment model of scientific studies *Proceedings of the 9th Illia O. Teplytskyi Workshop on Computer Simulation in Education (CoSinE 2021) co-located with 17th International Conference on ICT in Education, Research, and Industrial Applications: Integration, Harmonization, and Knowledge Transfer (ICTERI 2021), Kherson, Ukraine, October 1, 2021* (*CEUR Workshop Proceedings* vol 3083) ed Kiv A E, Semerikov S O, Soloviev V N and Striuk A M (CEUR-WS.org) pp 43–58 URL https://ceur-ws.org/Vol-3083/paper278.pdf
[95] Shchokin V and Shchokina O 2015 *Metallurgical and Mining Industry* **7**(2) 11 – 18
[96] Shkarupylo V V, Tomičić I and Kasian K M 2016 *Journal of Information and Organizational Sciences* **40**(1) 145 – 152 URL https://doi.org/10.31341/jios.40.1.7
[97] Cuevas K, Chougan M, Martin F, Ghaffar S H, Stephan D and Sikora P 2021 *Journal of Building Engineering*

44 102718 ISSN 2352-7102 URL https://doi.org/10.1016/j.jobe.2021.102718

[98] Vladimirov V A, Ma¸czka C, Sergyeyev A and Skurativskyi S 2014 *Communications in Nonlinear Science and Numerical Simulation* **19**(6) 1770–1782 ISSN 1007-5704 URL https://doi.org/10.1016/j.cnsns.2013.10.027

[99] Poros M and Sobczyk W 2014 *Rocznik Ochrona Srodowiska* **16**(1) 386 – 403

[100] Danchenko Y, Andronov V, Sopov V, Khmyrov I and Khryapynskyy A 2018 *MATEC Web of Conferences* **230** 03004 URL https://doi.org/10.1051/matecconf/201823003004

[101] Stanytsina V, Artemchuk V, Bogoslavska O, Zaporozhets A, Kalinichenko A, Stebila J, Havrysh V and Suszanowicz D 2022 *Energies* **15**(19) 7215 ISSN 1996-1073 URL https://doi.org/10.3390/en15197215

[102] Stoliarenko V, Chernova M and Yakovchuk O 2020 *E3S Web of Conferences* **166** 01005 URL https://doi.org/10.1051/e3sconf/202016601005

[103] Shapovalova N, Rybalchenko O, Dotsenko I, Bilashenko S, Striuk A and Saitgareev L 2019 Adaptive Testing Model as the Method of Quality Knowledge Control Individualizing *Proceedings of the 15th International Conference on ICT in Education, Research and Industrial Applications. Integration, Harmonization and Knowledge Transfer. Volume II: Workshops, Kherson, Ukraine, June 12-15, 2019* (*CEUR Workshop Proceedings* vol 2393) ed Ermolayev V, Mallet F, Yakovyna V, Kharchenko V S, Kobets V, Kornilowicz A, Kravtsov H, Nikitchenko M S, Semerikov S and Spivakovsky A (CEUR-WS.org) pp 984–999 URL https://ceur-ws.org/Vol-2393/paper_328.pdf

[104] Timchenko R A, Krishko D A, Holovko S I, Goodary R and Aniskin A 2022 *IOP Conference Series: Earth and Environmental Science* **1049**(1) 012032 URL https://doi.org/10.1088/1755-1315/1049/1/012032

[105] Toderaş M, Moraru R I and Popescu-Stelea M 2015 *Journal of Mining Science* **51**(3) 541–552 ISSN 1573-8736 URL https://doi.org/10.1134/S1062739115030163

[106] Tomiczek K 2019 *IOP Conference Series: Earth and Environmental Science* **261**(1) 012055 URL https://doi.org/10.1088/1755-1315/261/1/012055

[107] Merzlykin O V, Topolova I Y and Tron V V 2018 Developing of Key Competencies by Means of Augmented Reality at CLIL Lessons *Proceedings of the 1st International Workshop on Augmented Reality in Education, Kryvyi Rih, Ukraine, October 2, 2018* (*CEUR Workshop Proceedings* vol 2257) ed Kiv A E and Soloviev V N (CEUR-WS.org) pp 41–52 URL https://ceur-ws.org/Vol-2257/paper05.pdf

[108] Tsyganenko-Dzyubenko I Y, Ghandzyura V, Alpatova O, Demchyk L, Khomyak I and Vovk V 2023 *Ekolohichni nauky* (1(46)) 53–58 URL https://doi.org/10.32846/2306-9716/2023.eco.1-46.9

[109] Panchenko L F, Vakaliuk T A and Vlasenko K V 2020 Augmented reality books: concepts, typology, tools *Proceedings of the 3rd International Workshop on Augmented Reality in Education, Kryvyi Rih, Ukraine, May 13, 2020* (*CEUR Workshop Proceedings* vol 2731) ed Burov O Y and Kiv A E (CEUR-WS.org) pp 283–296 URL https://ceur-ws.org/Vol-2731/paper16.pdf

[110] Demeuov A, Tilekova Z, Tokpanov Y, Hanchuk O, Panteleeva N and Varfolomyeyeva I 2021 *E3S Web of Conferences* **280** 11010 URL https://doi.org/10.1051/e3sconf/202128011010

[111] Vlasenko K, Hrudkina N, Reutova I and Chumak O 2018 *Eastern-European Journal of Enterprise Technologies* **3**(1-93) 51 – 59 URL https://doi.org/10.15587/1729-4061.2018.131766

[112] Zotsenko M, Vynnykov Y, Doubrovsky M, Oganesyan V, Shokarev V, Syedin V, Shapoval S, Poizner M, Krysan V and Meshcheryakov G 2013 Innovative solutions in the field of geotechnical construction and coastal geotechnical engineering under difficult engineering-geological conditions of Ukraine *18th International Conference on Soil Mechanics and Geotechnical Engineering: Challenges and Innovations in Geotechnics, ICSMGE 2013* vol 3 p 2645 – 2648

[113] Didora V, Romantschuk L, Kliuchevych M, Vyshnivskyi P and Matviichuk N 2023 *Scientific Horizons* **25**(12) 60 – 68 URL https://doi.org/10.48077/scihor.25(12).2022.60-68

[114] Shkitsa L, Yatsyshyn T, Lyakh M and Sydorenko O 2020 *IOP Conference Series: Materials Science and Engineering* **749**(1) 012009 URL https://doi.org/10.1088/1757-899X/749/1/012009

[115] Shepiliev D S, Modlo Y O, Yechkalo Y V, Tkachuk V V, Mintii M M, Mintii I S, Markova O M, Selivanova T V, Drashko O M, Kalinichenko O O, Vakaliuk T A, Osadchyi V V and Semerikov S O 2020 *CEUR Workshop Proceedings* **2832** 84 – 93

[116] Shevchuk S, Zaichenko S, Opryshko V and Adjebi A 2019 Determination of the Diagnostic System Inertial Parameters for Power Generating Station Combustion Engine *2019 IEEE 6th International Conference on Energy Smart Systems (ESS)* pp 88–91 URL https://doi.org/10.1109/ESS.2019.8764170

[117] Zachosova N, Kutsenko D and Koval O 2022 *Financial and Credit Activity: Problems of Theory and Practice* **4**(45) 223 – 233 URL https://doi.org/10.55643/fcaptp.4.45.2022.3819

[118] Baranov G, Komisarenko O, Zaitsev I O and Chernytska I 2021 S.M.A.R.T. Technologies for Transport Tests Networks, Exploitation and Repair Tools *2021 International Conference on Artificial Intelligence and Smart Systems (ICAIS)* pp 621–625 URL https://doi.org/10.1109/ICAIS50930.2021.9396055

[119] Eremenko V S, Zaporozhets A O, Isaenko V and Babikova K 2019 Application of Wavelet Transform for

Determining Diagnostic Signs *Proceedings of the 15th International Conference on ICT in Education, Research and Industrial Applications. Integration, Harmonization and Knowledge Transfer. Volume I: Main Conference, Kherson, Ukraine, June 12-15, 2019* (*CEUR Workshop Proceedings* vol 2387) ed Ermolayev V, Mallet F, Yakovyna V, Mayr H C and Spivakovsky A (CEUR-WS.org) pp 202–214 URL https://ceur-ws.org/Vol-2387/20190202.pdf

[120] Yorkina N V, Podorozhniy S M, Velcheva L G, Honcharenko Y V and Zhukov O V 2020 *Biosystems Diversity* **28**(2) 181 – 194 URL https://doi.org/10.15421/012024

[121] Kulyk M, Nechaieva T, Zgurovets O, Shulzhenko S and Maistrenko N 2023 Comparative analysis of energy-economic indicators of renewable technologies in market conditions and fixed pricing on the example of the power system of ukraine *Systems, Decision and Control in Energy IV: Volume I. Modern Power Systems and Clean Energy* ed Zaporozhets A (Cham: Springer Nature Switzerland) pp 433–449 ISBN 978-3-031-22464-5 URL https://doi.org/10.1007/978-3-031-22464-5_26

[122] Stanytsina V, Artemchuk V, Bogoslavska O, Zinovieva I and Ridei N 2021 *E3S Web of Conferences* **280** 09012 URL https://doi.org/10.1051/e3sconf/202128009012

[123] Zarich V N and Marchenko B G 2002 *Izvestiya Vysshikh Uchebnykh Zavedenij. Radioelektronika* **45**(8) 12 – 18

[124] Kuzminska O 2021 *Educational Technology Quarterly* **2021**(3) 402–414 URL https://doi.org/10.55056/etq.19

[125] Shapovalov Y, Shapovalov V, Tarasenko R, Bilyk Z, Shapovalova I, Paschke A and Andruszkiewicz F 2022 *Educational Technology Quarterly* **2022**(3) 216–231 URL https://doi.org/10.55056/etq.40

[126] Kiv A, Semerikov S and Soloviev V 2021 *Educational Technology Quarterly* **2021**(2) 140–256 URL https://doi.org/10.55056/etq.54

[127] Semerikov S, Osadchyi V and Kuzminska O 2021 *Educational Technology Quarterly* **2021**(4) 429–604 URL https://doi.org/10.55056/etq.53

[128] Semerikov S 2021 *Educational Technology Quarterly* **2021**(1) 1–50 URL https://doi.org/10.55056/etq.13

[129] Trubavina I, Vorozhbit-Gorbatyuk V, Shtefan M, Kalina K and Dzhus O 2021 *Educational Technology Quarterly* **2021**(1) 51–72 URL https://doi.org/10.55056/etq.56

[130] Pinchuk N, Pinchuk O, Bondarchuk O, Balakhtar V, Balakhtar K, Onopriienko-Kapustina N, Shyshkina M and Kuzminska O 2022 *Educational Technology Quarterly* **2022**(2) 129–142 URL https://doi.org/10.55056/etq.8

[131] Vakaliuk T, Spirin O, Korotun O, Antoniuk D, Medvedieva M and Novitska I 2022 *Educational Technology Quarterly* **2022**(3) 232–250 URL https://doi.org/10.55056/etq.32

[132] Klochko O V and Fedorets V M 2022 *Educational Technology Quarterly* **2022**(4) 276–306 URL https://doi.org/10.55056/etq.431

[133] Burov O Y and Pinchuk O P 2023 *Educational Technology Quarterly* **2023**(1) 58–68 URL https://doi.org/10.55056/etq.435

[134] Shapovalov Y, Shapovalov V, Shapovalov B and Antonenko P 2022 *Educational Technology Quarterly* **2022**(2) 169–181 URL https://doi.org/10.55056/etq.3

[135] Prokhorov O V, Lisovichenko V O, Mazorchuk M S and Kuzminska O H 2022 *Educational Technology Quarterly* **2022**(4) 366–387 URL https://doi.org/10.55056/etq.430

[136] Vakaliuk T, Spirin O and Kontsedailo V 2021 *Educational Technology Quarterly* **2021**(1) 73–86 URL https://doi.org/10.55056/etq.16

[137] Hrynevych L, Morze N, Vember V and Boiko M 2021 *Educational Technology Quarterly* **2021**(1) 118–139 URL https://doi.org/10.55056/etq.24

[138] Vakaliuk T 2021 *Educational Technology Quarterly* **2021**(2) 257–273 URL https://doi.org/10.55056/etq.17

[139] Martyniuk O O, Martyniuk O S, Pankevych S and Muzyka I 2021 *Educational Technology Quarterly* **2021**(3) 347–359 URL https://doi.org/10.55056/etq.39

[140] Oleksiuk V and Oleksiuk O 2021 *Educational Technology Quarterly* **2021**(4) 605–616 URL https://doi.org/10.55056/etq.36

[141] Burov O 2021 *Educational Technology Quarterly* **2021**(4) 689–700 URL https://doi.org/10.55056/etq.43

[142] Kuchyn Y, Naumenko O, Vlasenko O, Lytvynova S, Burov O, Kucherenko I and Mykytenko P 2022 *Educational Technology Quarterly* **2022**(1) 73–87 URL https://doi.org/10.55056/etq.10

[143] Kukharenko V, Shunevych B and Kravtsov H 2022 *Educational Technology Quarterly* **2022**(1) 1–19 URL https://doi.org/10.55056/etq.4

[144] Gayevska O and Kravtsov H 2022 *Educational Technology Quarterly* **2022**(2) 105–114 URL https://doi.org/10.55056/etq.7

[145] Iyer S S, Gernal L, Subramanian R and Mehrotra A 2023 *Educational Technology Quarterly* **2023**(1) 18–57

URL https://doi.org/10.55056/etq.29
[146] Vakaliuk T A, Chyzhmotria O V, Chyzhmotria O H, Didkivska S O and Kontsedailo V V 2023 *Educational Technology Quarterly* **2023**(1) 106–120 URL https://doi.org/10.55056/etq.37
[147] Pinchuk O P and Luparenko L A 2023 *Educational Technology Quarterly* **2023**(2) 141–156 URL https://doi.org/10.55056/etq.582
[148] Nechypurenko P P, Chernova M P, Evangelist O O and Selivanova T V 2023 *Educational Technology Quarterly* **2023**(2) 188–209 URL https://doi.org/10.55056/etq.603
[149] Shapovalov Y B, Bilyk Z I, Usenko S A, Shapovalov V B, Postova K H, Zhadan S O and Antonenko P D 2023 *Educational Technology Quarterly* **2023**(2) 210–232 URL https://doi.org/10.55056/etq.604
[150] Bilyk Z I, Shapovalov Y B, Shapovalov V B, Megalinska A P, Zhadan S O, Andruszkiewicz F, Dołhańczuk-Śródka A and Antonenko P D 2022 *Educational Technology Quarterly* **2022**(4) 328–346 URL https://doi.org/10.55056/etq.433
[151] Vakaliuk T, Pilkevych I, Fedorchuk D, Osadchyi V, Tokar A and Naumchak O 2022 *Educational Technology Quarterly* **2022**(2) 143–151 URL https://doi.org/10.55056/etq.1
[152] Yelemessov K K, Baskanbayeva D D, Sabirova L B and Akhmetova S D 2023 Justification of an acceptable modern energy-efficient method of obtaining sodium silicate for production in Kazakhstan *IOP Conference Series: Earth and Environmental Science*
[153] Saveliev S G and Kondratenko M M 2023 Investigation of the influence of lime content in the charge and its quality on the sintering process of iron ore raw materials *IOP Conference Series: Earth and Environmental Science*
[154] Krivenko P, Rudenko I, Konstantynovskyi O and Razsamakin A 2023 Sustainable performance of alkali-activated blast furnace cement concrete with high freeze-thaw resistance *IOP Conference Series: Earth and Environmental Science*
[155] Sanytsky M, Kropyvnytska T and Ivashchyshyn H 2023 Sustainable modified pozzolanic supplementary cementitious materials based on natural zeolite, fly ash and silica fume *IOP Conference Series: Earth and Environmental Science*
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[157] Chubenko V A, Saveliev S G, Khinotska A A, Yarosh T P and Kondratenko M M 2023 Influence of deformation degree on grains size and borders between them in metal alloys during cold rolling of sheets *IOP Conference Series: Earth and Environmental Science*
[158] Ponomarenko O I, Yevtushenko S D, Yevtushenko N S, Berlizieva T V and Vorobiov M M 2023 Robust methods for controlling casting processes and the quality of castings *IOP Conference Series: Earth and Environmental Science*
[159] Skidin I E, Vodennikova O S, Saithareiev L N, Baboshko D Y and Barmenshinova M B 2023 Technology of forming a wear-resistant thermite alloy layer based on the Fe-Cr-C system by self-propagating high-temperature synthesis *IOP Conference Series: Earth and Environmental Science*
[160] Lebedeva K O, Cherkashina A M, Tykhomyrova T S, Savchenko D O and Lebedev V V 2023 Design and researching of biologically active polymeric hydrogel transdermal materials modified by humic acid *IOP Conference Series: Earth and Environmental Science*
[161] Lebedev V V, Miroshnichenko D V, Kryvobok R V, Cherkashina A M and Riabchenko M O 2023 Ceramic-inorganic polymer composites for protection against electromagnetic radiation mechanical properties designing *IOP Conference Series: Earth and Environmental Science*
[162] Dmytrenko V I and Diachenko Y H 2023 Enhancing the quality of the initial discovery of carbonate gas deposits in the Zahoryanska field zone by improving the drilling mud *IOP Conference Series: Earth and Environmental Science*
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[167] Vynokurova S, Yakovliev M, Voloshkevich O, Haidash O and Demchenko V 2023 Biodiversity assessment of the Danube region as a tool for the development of protected areas in the region *IOP Conference Series:*

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[168] Pyurko O E, Khrystova T E, Pyurko V E and Arabadzhi-Tipenko L I 2023 Seeds' similarity of cultural and natural flora under chloride load in conditions of southern Ukraine *IOP Conference Series: Earth and Environmental Science*
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[172] Mytiai I S, Khomych V V, Degtyarenko E V, Shevchenko P H and Martiusheva O O 2023 Impact of mini-hydropower on the chemical composition of water and phytoplankton of the reservoirs of the Forest-Steppe of Ukraine *IOP Conference Series: Earth and Environmental Science*
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Investigation of the influence of lime content in the charge and its quality on the sintering process of iron ore raw materials

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Investigation of the influence of lime content in the charge and its quality on the sintering process of iron ore raw materials

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Abstract. Main objectives of the work was to study the influence of degree of roasting of lime contained in the charge on the sintering process and sinter quality, as well as comparing the impact of changes in the mass fraction of active CaO in the charge by varying degrees of burning lime, and by varying the content of lime in the charge. It is shown that the intensifying effect of lime on the sintering process occurs as a result of a decrease in the content of small classes in the charge. When the lime content in the charge is equal to 3 %, an increase in the degree of lime firing from 5 to 96 % led to an increase in the specific productivity of the plant from 0.96 to 1.87 $t/(m^2 \cdot hour)$. The independence of sintering parameters from the content of active CaO in lime with its constant content in the sinter charge and the decisive role of the content of active CaO in the sinter charge with its constant content in lime are confirmed. A new approach to the production of lime for agglomeration processes is proposed: it should have the lowest cost of the active CaO contained in it.

1. Introduction

One of the conditions of the sustainable future is the quality improvement and the increase in production of ferrous metals, the vast majority of which are molten by two-stage scheme "cast iron – steel". Therewith in the worldwide iron making industry, sinter constitutes the major component in the metallic burden of most of the blast furnaces as it has numerous properties which lead to reduced coke rate, increased productivity, better heat transfer and permeability, elimination of raw flux, narrowing of softening and melting zones and better quality of hot metal. The sintering process is greatly influenced by the physico-chemical properties of raw materials used, whose characteristics change from time to time [1].

Lime is an important component of sintering charge. It provides the intensification of sintering and improves the quality of sinter. Therefore, the issue of the efficiency increasing of lime usage in the sintering production demands constant attention from workers and researchers. Thus, in Bhilai Steel Plant, Steel Authority of India Limited, a pilot sintering unit has been established in order to conduct experiments for subsequent application in industrial sinter manufacturing. Studies were taken up to assess the effect of quicklime addition in sinter-mix on sintering process of iron ore fines [1]. The results found have been encouraging with significant increase in productivity.

Efficiency of lime's utilization in iron ore materials' sintering depends on number of factors, the most important of which are the composition of sinter charge, the quality and quantity of used lime. A direct relationship is usually observed between the productivity of sintering machines and the consumption of lime, however, at high consumption of lime, a decrease in the strength of the agglomerate and an increase in the amount of fines in it are noted. In fact, to ensure high productivity of sintering machines and sinter quality, the optimal lime consumption should be determined individually, depending on the component composition of the sinter charge, the properties of charge materials and the features of the processing line for preparing the charge, starting from the averaging warehouse.

The decisive factor that determines the optimal consumption of lime introduced into the sinter batch is the mass fraction of the assimilated charge of lime, that is, slaked and passed the stage of dispersion. The influence of this factor is primarily associated with the technology of moistening the charge and with the design and technological parameters of the used mixing equipment [2].

At the same time, the mass fraction of the lime assimilated by the charge depends on the content of active components in the lime – calcium and magnesium oxides, that is, on the quality of the lime. The required quality of metallurgical sinter is provided by the valid choice of the raw material with optimal chemical and granulometric composition and specific selection of tackle [3]. When choosing a kiln and assigning thermal modes, it is necessary to be guided by the results of control calcinations of lime and analyzes of the batching capacity of lime.

The core indicator of a lime's quality is the content of active CaO, which determines the degree of lime burning. It is acknowledged [4], that lime, which is used in sintering for the intensification of sintering thin iron ore concentrates, must contain not less than 80 % of $CaO + MgO$, and the size of seeds must be $3-0$ mm.

With the aim of achieving required lime size in the conditions of sintering production OJSC "Ural Steel" it has been suggested [5] to upgrade the lime preparation section via closed cycle actualization of lime grinding with an installation of a hammer mill and screening machine (to separate lime into fractions –3 and +3 mm).

The CaO content in lime is sometimes [6] called a purity degree of lime, which was received after the limestone burning. This marker depends not only on the degree of dissociation of Calcium Carbonate but also on the degree of purification of initial limestone.

2. Literature review

The laboratory sinter burnings in Raw Materials Research Center OJSC "Severstal" with the use of lime showed [7] that the dependence of charge pelletization degree on the content of lime in it is extreme. The dependence of the charge sintering rate on the lime content in it also has an extreme nature. The greatest rate of sinter charge which is equal to 16.65 mm/min is obtained by the lime consumption of 28 kg/ton.

In the laboratory and manufacturing conditions the optimal consumption of lime into PJSC "Novolipetsk Metallurgical Plant" (NLMP) sinter charge was determined with consideration of the process of lime hydration and the difference between the amount of water and supreme molecular moisture capacity [2]. It was determined that the exceedance of optimal liming level deteriorates a sinter quality.

The research of the lime mass fraction in JSC "ArcelorMittal Temirtau" sinter charge impact on the process of its pelletization research showed [8] that increasing lime content in charge from 1 to 5 % a percentage of thin fraction in charge 1.6–0 mm which influences negatively on the sintering speed decreases from 18 to 5 %.

Theoretical and technological incentives to use lime in the sinter charge were examined in detail in monographies [9, 10]. The presented results of the impact of lime's quantity in charge correspond to the above-mentioned data.

A significant lime's qualitative characteristic is its reactivity, in other words – rate of hydration that depends on the lime's method of firing and the content of the environment's gaseous state composition. The work [11] demonstrates that industrial furnace calcining largelimestone pellets leads to low reactivity quicklimes both because the calcination temperatureis too high and the CO_2 pressure is too elevated.

To improve a firing thermal behavior on a conveyor it has been suggested [12,13] to use definite proportions of classified lime fractions and solid fuel. In the conditions of PJSC "Metallurgical Plant "Zaporizhstal" the use of improved technology will improve the technical and economic performance of the limestone burning process.

To evaluate the hydration characteristics of the lime, the Constant-temperature Calorimetric Method (CCM) has been used to test four types of lime from the sintering plant, and the granulation and sintering pot test was conducted to validate the results of CCM [14]. It showed that the CCM can precisely test the hydration heat and hydration speed of the lime and avoid the shortage of the tradition ways, and the hydration speed of lime is positively related to granulating effect and sintering productivity. The hydration properties of the four types of lime were remarkably different, the whole hydration heat is positively related with the CaO content of the lime, but the hydration speed is more influenced by the impurities and the microstructure of the lime. In this case, the increasing of the SiO_2 and MgO content can reduce the hydration speed of the lime, and the Al_2O_3 has two way effects. The lime with fine crystal grain size has a large hydration speed.

As can be seen from the above the analysis demonstrates that the lime's impact on a sintering process depends on the charge conditions and the quality of lime, but the reciprocal proportion's impact of this factors have not been examined yet.

3. Problem formulation

Based on the above, in this work were set following tasks:

- to study the impact of the lime burning degree on a sintering process and sinter quality;
- to compare the impact of CaO in charge based on the lime burning degree change and lime content change in charge.

4. Methods

The impact of the lime burning degree on a sintering process and a sinter quality from ArcelorMittal Kryvyi Rih sinterplant's charge was examined in laboratory settings.

The chemical composition of charge components is listed in table 1.

Table 1. The composition of charge materials.

Material	Chemical composition, %								
	Fe_{total}	FeO	SiO_2	CaO	CaO_{act}	MgO	MnO	C	Loss on ignition
Concentrate	65.1	23.5	7.7	0.4	—	0.49	0.20	—	0.94
Agloore	53.3	0.8	11.35	0.46	—	0.37	0.12	—	3.35
Limestone	1.45	0.45	1.7	51.13	—	2.82	No data	—	43.17
Lime I	No data	No data	1.96	59.0	23.6	3.26	No data	—	27.8
Lime II	No data	No data	2.05	61.8	30.9	3.41	No data	—	24.8
Lime III	No data	No data	2.34	70.04	52.8	3.88	No data	—	13.8
Fuel	2.6	0.04	6.89	0.79	—	0.26	0.10	81.36	No data
Manganese ore	4.4	0.15	19.65	6.64	—	1.81	15.9	—	18.69
Return	50.4	9.6	10.5	8.4	—	1.0	1.33	1.64	No data

The quicklime with the grain-size 3-0 mm, which was obtained from limestone burning in an experimental-industrial cyclone furnace was used. The different lime burning degree was obtained by the mode change of furnace.

Mixing and pelletization of charge with the simultaneous moistening up to 7.8 – 8.2 % were proceeded in a drum 0.6×1.0 m in size during 8 min. Pelletized charge was burned in a sintering bowl with an area of 0.132 m^2, in a form of layer of 280 mm in height.

The rarefaction under the grate of the sintering bowl in a sintering process was maintained permanent and equal to 11.28 kPa (∼ 1150 mm water column). The preparation conditions of the sinter charge and the mode of its sintering during the research were the same. Each experiment, which included assembling, preparing and sintering the sinter charge, was repeated 3-5 times.

In order to compare the impact of the active CaO content in lime, at a constant flow rate in the charge, sintering was performed with the same types of lime, setting them in the charge in the same amount – 3 % of the charge‘s weight. In this set of sintering, the content of active CaO in sinter charges was 0.71; 0.93 and 1.58 %, respectively.

To test the assumption of the determining impact on the sinter process of the amount of active CaO which is being added by lime into the charge, regardless of the lime burning degree, sintering was performed at a constant content of active CaO in the sinter charge, which was equal to 1.26 %. Herewith was used a lime with a degree of firing of 40, 50, 75 and 96 %, the content of which in the sinter charge in each case was 5.3; 4.1; 2.4 and 1.6 %, respectively.

5. Analysis

The main results of sintering with lime content in the sinter charge of 3 % at different burning degrees are shown in figures 1 - 5.

The intensifying effect of lime on the sintering process is associated, first of all, with a decrease in the gas-dynamic resistance of the pelletized charge layer due to a decrease in the content of small classes (figure 1) and an increase in the strength of individual pellets.

This is due to the viscous properties of lime, hydration hardening of which is carried out according to the scheme of dissolution – colloidization – crystallization. When the content of lime in the sinter charge of 3 % increase in the degree of firing of lime from 5 to 96 %

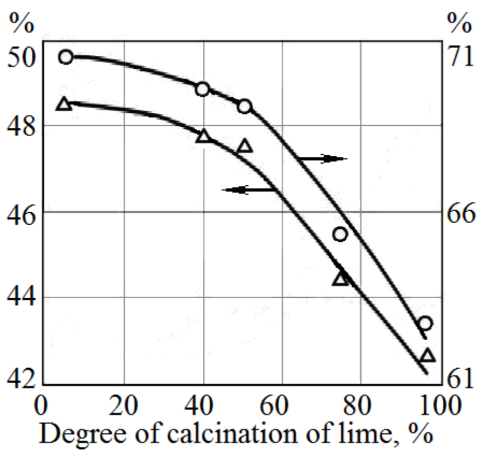

Figure 1. The influence of the lime burning degree on the indicators of palletization: content of class –3 mm (△) and –5 mm (○) in the pelletized charge, %.

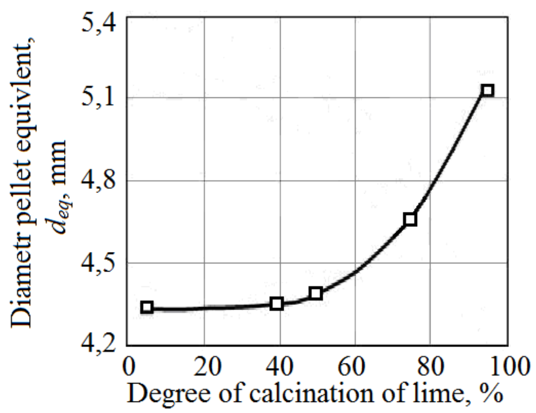

Figure 2. The influence of the lime burning degree on the equivalent diameter of pelletized pellets.

(corresponding to an increase in the content of CaO active in the charge from 0.08 to 2.30 %) led to a decrease in the content of classes 5 - 0 and 3 - 0 mm in the lump charge from 70.7 to 62.7 % and from 48.5 to 42.8 %, respectively. The equivalent diameter of the granules of the pelletized charge, calculated as a weighted average by weight, increased from 4.38 to 5.14 mm (figure 2).

A similar result of the effect of the lime content in the charge on the sintering performance was obtained in [15], in which the positive effect of adding up to 2 % quicklime to the sinter charge on its gas permeability was experimentally established. A further increase in the lime content in the charge no longer improves its pelletizing. The lower value of the maximum allowable lime content in the charge in [15] compared to the conditions in this study is explained by differences in the composition of the ore part of the sinter charge.

The decrease of the sinter charge gas-dynamic resistance leads to an increase in the specific air flow rate on sintering, as a result of what the vertical sintering rate and the specific productivity of the sinter plant continuously increase (figure 3).

The sintering rate during the experiments changed more than twice, and the specific productivity – from 0.96 to 1.87 t/(m^2·hour). That is, for each percent of the lime burning degree increase, the specific productivity of the installation increased by an average of almost 0.96 %. A slightly smaller change in the specific productivity compared to the sintering rate is associated with the influence of variable when using lime of different bulk weight burning degrees of the pelletized charge and the yield of a suitable sinter after sintering.

The yield of the +5 mm class after double dumping of the sinter pie from a height of 2 m while increasing the lime burning degree tends to decrease (figure 4).

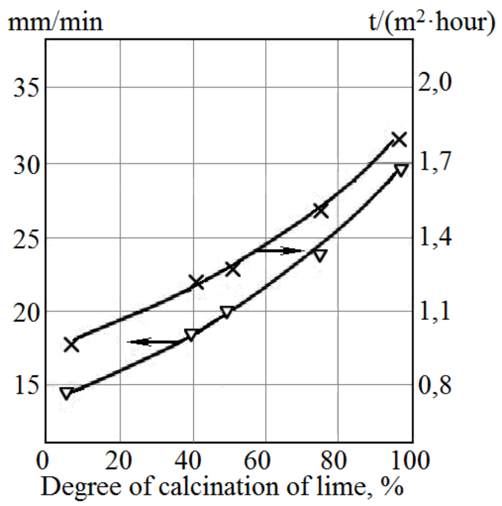

Figure 3. The influence of the lime burning degree on the indicators of sintering: vertical sintering speed (▽), mm/min; specific productivity (×), t/(m^2·hour).

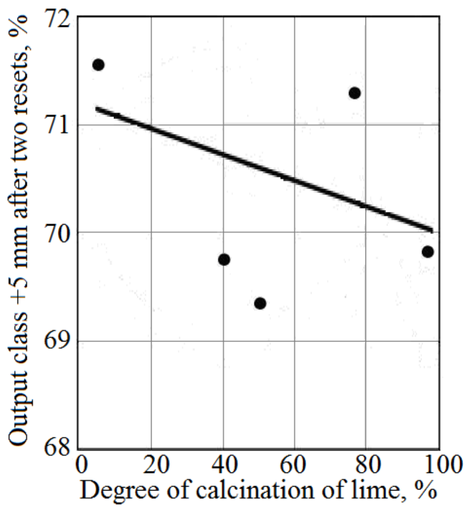

Figure 4. The influence of the lime burning degree on the indicators of the strength of the sinter after two resets.

The dependence of test results of sinter in the drum on the lime burning degree is extreme (figure 5), which is obviously caused by a change with the increase in the degree of calcination of lime, the ratio between the development of processes that have the opposite effect on the strength of the sinter.

Comparison of the results obtained with similar studies of obtaining agglomerate with basicity (CaO/SiO_2) equal to 1.7 under the conditions of PJSC NLMK [2] confirms the extreme nature

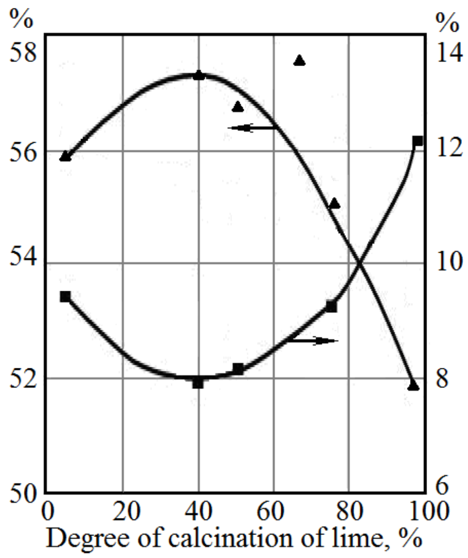

Figure 5. The influence of the lime burning degree on the indicators of the strength of the sinter after the drum test: output class +5.0 mm (▲) and −0.5 mm (■) after the drum, %.

of the dependence of the cold strength of the agglomerate on the mass fraction in the charge of active components of lime (or the content of lime in the charge). The highest strength is obtained when lime is introduced into the charge in an amount of 25 - 30 kg/t of sinter.

Factors that increase the strength of the sinter with increasing the lime burning degree – improving the conditions of mineral formation in the heating zone and improving the conditions of melt formation, reducing the melt viscosity, increasing the sintering temperature due to reduced heat consumption for decomposition of calcium compounds (FeO content in the agglomerate with increasing the lime burning degree increased from 10.0 to 13.1 %) – prevail at the lime burning degree up to about 40 %. The sinter obtained with the use of lime with a burning degree of 35 – 45 % has the best indicators of strength, both on impact and on abrasion. A further increase in the lime burning degree causes a decrease in the sinter test performance in the drum due to the predominant effect on the cooling rate of the sinter, which increases simultaneously with the vertical sintering rate, that is accompanied by an increase in vitreous phases and internal stresses in the sinter structure. Thus, increasing the lime burning degree from 40 to 96 % led to a decrease in the resistance of the sinter to impact from 57.6 to 51.9 % and abrasion from 7.9 to 12.2 %.

It should be borne in mind that another reason for the decrease in the strength of the agglomerate when a certain level of lime consumption in the charge is exceeded may be an insufficient degree of assimilation of the active components by the lime charge. This is due to the emergence of a water deficit in the charge not only for hydration of lime at the stage of preparing the charge for pelletizing, but also for pelletizing the charge [2].

The main results of the experiments confirm the independence of sintering indicators from the content of active CaO in lime at a constant content in the sinter charge (figure 6, figure 7) and the decisive impact of the active CaO content in the sinter at a constant content in lime (figure 7, figure 8).

At the same time, with an increase in the active CaO concentration in the sinter charge in the range of 0.71 - 1.58 %, the sintering rate and specific productivity continuously increase (figure 8), as well as the drum testindicators decrease (figure 9).

This is due to the complex nature of the impact of active CaO in the sinter charge on the strength of the sinter. With the increase of active CaO in the sinter charge simultaneously with the development of processes that increase strength, the development get the processes that reduce it; in particular, the number of vitreous phases and the level of internal stresses in the

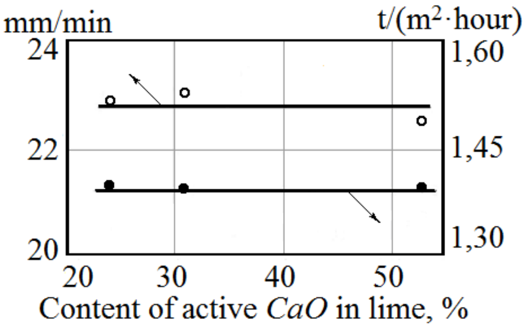

Figure 6. The impact of the active CaO content in lime on the sintering process at a constant content of active CaO in the sinter charge (1.26 %): sintering speed, mm/min (○); specific productivity, t/(m^2·hour) (●).

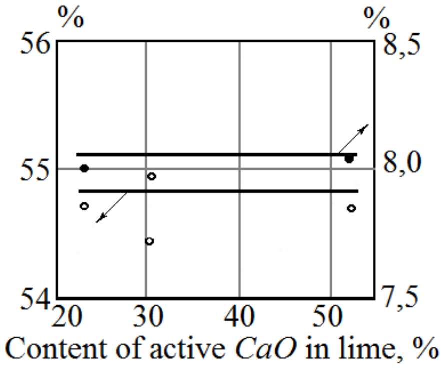

Figure 7. The impact of the active CaO content in lime on the indicators of the strength of the sinter after the drum test at a constant content of active CaO in the sinter charge (1.26 %): output of class +5.0 mm after the drum, % (○); output of class −0.5 mm after the drum, % (●).

structure of the sinter increases as a result of increasing the cooling rate. Obviously, in the studied interval of increasing the active CaO content in the sinter charge at a given composition of the charge, the mode of its preparation and sintering, the processes that reduce the strength of the sinter predominate.

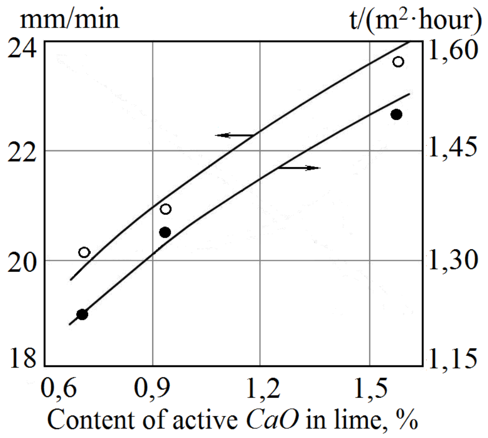

Figure 8. The influence of the content of active CaO in the sinter charge on the sintering process at a constant content of lime in the charge (3.0 %): sintering speed, mm/min (○); specific productivity, t/(m^2·hour) (●).

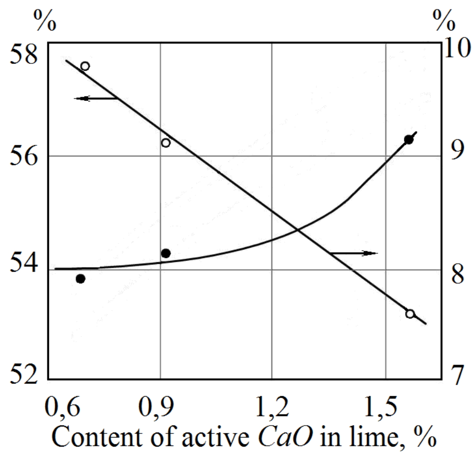

Figure 9. The influence of the content of active CaO in the sinter charge on the strength of the sinter after the drum test at a constant content of lime in the charge (3.0 %); output of class +5.0 mm after the drum, % (○); output of class −0.5 mm after the drum, % (●).

6. Discussion

In the article of Chinese researchers [16], the results of the study are presented, which complement the above-described mechanism of the intensifying effect of quicklime on the sintering process from the position of changing the structure of the sinter. The effect of quick lime on pore characteristics of the high-temperature zone in the iron ore sinter was studied. The equivalent spherical diameter of the pore and its distribution frequency, volume fraction, sphericity, and surface porosity were statistically analyzed. The results indicate that the addition of quick lime increases the permeability of the green bed and shortens the sintering time. With the increase of the addition of quick lime, the porosity of the sinter decreases gradually. 1With the increase of quick lime, the total pore volume and total pore length, the number of pore segments, branching nodes and terminal nodes all decrease.

Comparison of the obtained results with the literature data about the impact of lime content in the sinter charge with a constant burning degree on the sintering process [6, 7] indicates a similar nature of changes occurring in these cases, that is, when the content of active CaO in the charge is changes.

At the same time, from the standpoint of lime on the sintering process the burning degree change can be replaced by a corresponding change in its content in the charge and vice versa.

Since common in both cases is the change in the amount of active CaO by lime which is being added into the sinter charge, this particular indicator (or the amount of $Ca(OH)_2$ in the case of slaked lime) determines the effectiveness of lime under the other equal conditions. It can be noted that with the increasing lime content in the sinter charge, the lime burning degree, which corresponds to the maximum strength of the sinter, will decrease, and with the decreasing lime content – will increase.

7. Conclusions

Studies have shown the high efficiency of using lime as an intensifier of the sintering process. An increase in the amount of active CaO added by lime to the charge from 0.71 to 1.58 % leads to an increase in the specific productivity of the sinter plant from 0.96 to 1.87 t/(m^2·hour). The mechanism of the lime intensifying effect is associated with its positive impact on the process of charge pelletisation (reduction of the proportion of small fractions of 5-0 and 3-0 mm in the pelletised charge), which is accompanied by a decrease in the gas-dynamic resistance of the charge and a corresponding increase in the vertical sintering rate and specific productivity of the sinter plant.

On the basis of the conducted researches it is possible to draw a conclusion that the efficiency of the limestone replacement by lime at sintering is defined by the quantity of active CaO brought by lime in a sinter charge, and in this sense practically does not depend on the lime burning degree or its concentration in charge (with a constant mesh-size distribution of lime, permanent degree of quenching in the process of preparing charge to the sintering, constant lime distribution degree in charge and other equal conditions associated with the use of lime).

A similar pattern occurs when using lime as a binder in the production of pellets. This implies a new approach to the production of lime for pelletizing processes, which should be based on the technical and economic indicators of the unit for the production of lime. It is necessary to produce such lime, which has the lowest cost of active CaO contained in it. This means that it does not make sense to produce lime for pelletizing processes with a high burning degree, because the closer to the maximum possible burning degree, the more heat a single particle of calcium carbonate needs for decomposition. The rational degree of burning is usually 60-70 %.

Given the increase in the relative heat consumption for the decarbonization of $CaCO_3$ with increasing degree of its firing, it should be considered impractical to produce for the process of agglomeration of iron ore materials lime with the highest degree of firing. The optimum degree of lime firing should be about 60–70 %. The validity of this conclusion is confirmed in particular by the fact that in the pelletizing workshop of the Northern Mining and Processing Plant (NorthMPP) laboratory and industrial tests of pellet production using lime as a binder used quicklime, which contained 63 – 67 % $(CaO + MgO)_{act}$ [17].

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References

[1] Sharma A and Rai N 2010 Effect of burnt lime addition on sintering of iron ore fine *Proceedings of the XI International Seminar on Mineral Processing Technology (MPT-2010)* (NML Jamshedpur, India: CSIR-National Metallurgical Laboratory) URL https://eprints.nmlindia.org/2486/
[2] Filatov S V, Kurunov I F, Semenov O A, Mansurova N R and Kobelev V A 2014 *Stal'* **10** 7–9
[3] Golubev V O, Nikol'skij V E and Abezgauz B S 2008 *Metallurgist* **10** 52–58 URL https://naukarus.com/kontrol-i-vybor-optimalnyh-parametrov-tehnologii-proizvodstva-marochnoy-metallurgicheskoy-.izvesti-dlya-chernoy-metallurgi
[4] Monastyrev A and Galiakhmetov R 2011 *Furnaces for the production of lime* (Voronezh, Russia: Istoki)
[5] Shapovalov A N and Ovchinnikova E V 2013 *Mechanical Engineering: An Online Electronic Scientific Journal* **2** 34–39
[6] Novak S, Garmash N, Martyinenko V and Martyinenko A 2006 *Theory and practice of agglomeration process management* (Krivoy Rog, Ukraine: Southern Mining and Processing Plant (YuGOK))
[7] Kurkin V M, Tabakov M S, Kashkarov E A, Gurkin M A, Detkova T V and Reshetkin S V 2007 *Metallurgist* **8** 49–52 URL https://naukarus.com/vliyanie-izvesti-na-spekanie-agloshihty
[8] Dyakov A V, Odintsov A A, Kobelev V A and Nechkin E A 2018 *Ferrous metallurgy. Bulletin of scientific, technical and economic information* **10** 27–34 URL https://doi.org/10.32339/0135-5910-2018-10-27-34
[9] Oates J A H 2008 *Lime and Limestone: Chemistry and Technology, Production and Uses* (John Wiley & Sons)
[10] Bizhanov A and Chizhikova V 2019 *Agglomeration in Metallurgy* Topics in Mining, Metallurgy and Materials Engineering (Cham: Springer) URL https://doi.org/10.1007/978-3-030-26025-5
[11] Commandré J M, Salvador S and Nzihou A 2007 *Chemical Engineering Research and Design* **85**(4) 473–480 ISSN 0263-8762 URL https://www.sciencedirect.com/science/article/pii/S0263876207730708
[12] Gavrilko S A, Koval P P and Gavrilko Y S 2010 *Metallurgy* **21** 12–18
[13] Koval P P, Moseiko Y V, Kuris Y V, Vodennikova O S, Bezpalov R I, Kovalenko I V, Gromak G A, Lichkonenko N V and Tsvetkova E I 2016 *Metallurgy. Collection of scientific papers of the Zaporozhye State Engineering Academy* **2(36)** 10–15 URL https://dspace.znu.edu.ua/jspui/handle/12345/797
[14] Zhang L, Wu S, Zhang Y and Zhou M 2015 *AISTech - Iron and Steel Technology Conference Proceedings* **1** 471–480
[15] de Alencar J P S G and Campos Júnior F L C 2021 *Tecnol. Metal. Mater. Min.* **18** e2486 URL https://doi.org/10.4322/2176-1523.20212486
[16] Zhou H, Wang J, Ma P, Meng H, Cheng F and J L 2021 *Journal of Materials Research and Technology* **15** 4475–4486 URL https://doi.org/10.1016/j.jmrt.2021.10.061
[17] Zhuravlev F, Lyalyuk V, Stupnik N, Morkun V, Chuprinov E and Kassim D 2019 *Theory, technology and equipment for the production of pellets and new iron ore raw materials for blast furnace smelting* (Kryvyi Rih: Chernyavskiy D.A.)

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Justification of an acceptable modern energy-efficient method of obtaining sodium silicate for production in Kazakhstan

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Abstract. Sodium silicate is used in various industries. Sodium silicate is a basic component in the production of silicate adhesives and paints, silica gel, welding electrodes, corrugated packaging, and geopolymer concretes and cements. All this is currently not produced in the Republic of Kazakhstan. The article discusses the methods of production of sodium silicate and substantiates the possibility of organizing production in the Republic of Kazakhstan. The authors have studied all the available experience in the production of sodium silicate, both now and in the past. At this stage of the research, an analysis was made of the experience in the production of serial and pilot sodium silicate in the USSR in the past and in countries where development has not been suspended at the present time. All possible sources of raw materials of technogenic and natural origin were studied. Business trips and expeditions to natural deposits were carried out and samples of raw materials from various natural and man-made sources were delivered. Studies have been carried out to determine the available volumes of raw materials. Various technologies for melting sodium silicate have been studied, incl. by unconventional schemes, such as smelting in cyclone furnaces. For melting in electric furnaces, various schemes of energy-saving methods for melting sodium silicate were analyzed. Promising ones have been identified. The following types of sodium silicate production were analyzed in the study: traditional smelting (carbonate method), wet method, sodium chloride sublimation method, sulfate method, cullet smelting. The optimal variant has been chosen, which makes it possible to reduce the cost of electricity by several times when introducing a highly efficient innovative technology of electric melting into practice.

1. Introduction

Sodium silicate has found wide application in many industries. It is used as a component of the charge for the production of glass, a filler in the composition of lightweight cement mortars for cementing wells, in the production of heat-resistant and acid-resistant concrete. As for the chemical industry, sodium metasilicate is used in the production of detergents and cleaning agents, household chemicals (Henkel washing powder). It is also widely used in oil production (as a coagulant in the production of regenerating oil) and the textile industry, metallurgy, mechanical engineering. Sodium silicate is used as an inhibitor with a corrosive effect, for disinfection of premises, linen, dishes, plumbing. Interestingly, silicates are one of the components of precious stones (emerald, topaz, aquamarine). They are used as a fire-fighting impregnation for wood (decoration processing), a mixture of sawdust and silicate fills the gap between the walls of safes also to protect against fire [1–3].

Sodium silicate is a basic component in the production of silicate adhesives and paints, silica gel, welding electrodes, corrugated containers, and geopolymer concretes and cements [4, 5]. All this is currently not produced in the Republic of Kazakhstan. As for its use in the production of building materials, the technology is needed by all existing enterprises in the production of small-piece building materials, as well as all enterprises producing reinforced concrete products in regions where there are blast furnace or thermophosphoric slags [6–8].

The technology of production of foam concrete based on geopolymers using sodium silicate is of the greatest interest, since here the strength of foam concrete depends on the strength of the elementary bubble, which, as is known, can be 2-3 or even 4 times stronger than in the case of traditional foam concrete based on Portland cement [9].

It follows from the above that sodium silicate is a widely applicable and necessary component for some industries. Thus, liquid glasses are used as a component of cements – heterogeneous systems, as well as an inorganic adhesive. As a “bundle” or “cured bundle”, water-soluble silicates are used both for the manufacture of composite materials and coatings, and for gluing parts and assemblies of aggregates for various purposes.

In this regard, the authors have studied all available experience in the production of sodium silicate, both now and in the past. At this stage of research, the analysis of the experience of the production of sodium silicate, both serial and pilot-industrial in the USSR in the past and in countries with not suspended development at the present time, was carried out.

Various technologies are classified.

Further, all possible sources of raw materials of both man-made and natural origin were studied. Business trips and expeditions to natural deposits were carried out and samples of raw materials from various natural and man-made sources were delivered. Studies have been conducted to determine the available volumes of raw materials.

Various technologies for melting sodium silicate have been studied, including using unconventional schemes, such as melting in cyclone furnaces. For melting in electric furnaces, various schemes of energy-saving methods for melting sodium silicate were analyzed. Promising ones have been identified.

Polymer concretes made with the use of slag-alkali binders showed increased quality characteristics, such as: strength, frost resistance, heat resistance, durability and impermeability. However, there is a shortage of inexpensive alkaline components on the market of the Republic of Kazakhstan, which would speed up cation exchange processes in the astringent system and increase hydration activity.

In Kazakhstan, there are unlimited natural reserves of sodium sulfate, when melting with lime, soda melt (a mixture of soda and gypsum) is obtained, which is a necessary component of slag-alkaline binders.

Soluble sodium silicate (soluble glass or silicate block) is the most multi-tonnage product of inorganic chemistry and is used in many industries:

1) Geopolymers;
2) Corrugated cardboard, books and other printing products;
3) Welding electrodes (coating);
4) Refractory and acid-resistant concrete;
5) Foam glass;
6) Cement Chipboard;
7) Foam concrete;
8) When arranging waterproofing during construction work;

9) Silica gel (adsorbent);
10) In metallurgy for molding injection mixtures;
11) In mechanical engineering for bundles for briquetting metal chips;
12) Flotation reagents in the enrichment of non-ferrous metals, primarily zinc;
13) Soap and washing powder;
14) In the rubber industry as a raw material for white soot (rubber filler);
15) In the food industry as an emulsifier E550.

The authors are working in the field of reducing energy costs. For this purpose, the technology of reactive power compensation with a magnetic amplifier is proposed, which is key, can be used in hundreds and thousands of companies only in Kazakhstan, where there are significant unit costs for electricity – from mining to street lighting.

2. Materials and methods

Sodium silicate is the most multi-tonnage product of inorganic chemistry. The greatest interest in obtaining sodium silicate with a low cost is shown by manufacturers of geopolymer cements, which require it to produce clinker-free binders. In the production of conventional cement, up to 400 kg of coal is burned for each ton of clinker. At the same time, almost one and a half tons of carbon dioxide are emitted into the atmosphere. In the production of clinker-free cement, granular blast furnace slag is used, of which more than 50 million tons have been accumulated in Temirtau, and the clinker firing process is excluded. However, sodium silicate (aka silicate-block) is also required, when added in an amount of 6-10%, cement of the M800-M1000 brand is obtained! In addition to the construction materials industry, the silicate block is used in a variety of industries (construction, printing, production of corrugated packaging, in the production of adsorbents). Currently, it is not produced in the Republic of Kazakhstan. Usually, a silicate block is obtained by melting quartz sand with soda in bath-type gas furnaces. Such furnaces have a characteristic size of about 40 m and are very expensive due to the use of a large number of refractory materials [10].

The authors are conducting research in the field of possibilities to use an electric direct heating furnace, which provides the same result with dimensions, and, accordingly, the cost is an order of magnitude lower. Considered below are past and present experiences in the production of sodium silicate.

Traditional melting (carbonate method). Currently, most glass industry enterprises in the CIS countries use soda ash and/or mixed with sodium sulfate for melting silicate blocks (figure 1).

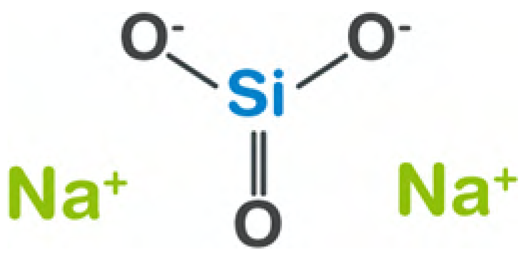

Figure 1. Structure of sodium silicate.

In a mixture with quartz sand, sodium carbonate (soda ash) or potassium carbonate are melted in flared glass furnaces of continuous operation. The reaction proceeds according to the following reaction:

$$n\mathrm{SiO_2} + \mathrm{Na_2CO_3} = \mathrm{Na_2O}\cdot n\mathrm{SiO_2} + \mathrm{CO_2}, \tag{1}$$

$$n\mathrm{SiO_2} + \mathrm{K_2CO_3} = \mathrm{K_2O}\cdot n\mathrm{SiO_2} + \mathrm{CO_2}. \tag{2}$$

This technology, firstly, requires significant capital expenditures for the construction of glass furnaces, so this method is unacceptable for our task. Secondly, the cost of soda ash at the level of 100 thousand tenge per ton with delivery to Karaganda also makes it impossible to fit into the specified cost range, since the amount of soda in the charge is 40%, i.e. the cost of soda alone will amount to 40 thousand tenge per 1 ton of sodium silicate [11].

We took a trip to Lake Tanatar (Altai Krai, Russia) to study the market in order to reduce the cost of soda ash. There is an enterprise for the extraction of natural soda. As will be further shown in paragraph 2 of this study, the use of natural soda from the Altai Krai is impractical.

Wet method. In China, where there are large enterprises for the production of soda ash, a wet method for producing liquid glass by dissolving finely ground quartz sand in a saturated solution of caustic soda is widespread [12].

The large source of amorphous silica available in Karaganda (waste from the production of the "Silicium Kazakhstan" plant) makes this production method very attractive, since the dissolution of amorphous silica occurs much faster and with lower energy costs than quartz sand. The reserves available at the landfill of the enterprise amounted to about 50 thousand tons in 2019. The cost was 3,000 tenge per ton. Part of the amorphous silica was purchased by us and studied at our request by Vladimir Merkulov, professor of the Karaganda State Industrial University for solubility in a 40% caustic soda solution in the laboratory of the Karaganda Industrial Institute. The result of the dissolution reaction was a liquid glass of black color, which is applicable for the production of slag-alkali cement.

However, the cost of caustic soda in the Republic of Kazakhstan at the level of 300 thousand tenge per 1 ton turned out to be unsuitable for any wet method technology due to the high cost.

The method of sublimation of sodium chloride. Of great practical interest are the works carried out in the USSR in the 50 s of the 20 th century on the production of sodium silicate by sublimation of sodium chloride in the presence of water vapor through quartz raw materials [13].

In this case, at temperatures of 600-1000 degrees Celsius, table salt and sodium ions react with quartz glass to produce sodium silicate:

$$\mathrm{NaCl}{+}n\mathrm{SiO_2} + \mathrm{H_2O} = 2\mathrm{HCl} + \mathrm{Na_2O}\cdot n\mathrm{SiO_2}. \tag{3}$$

This method is very attractive for practical implementation due to the low cost [14].

Due to the presence of a high content of unreacted silicon oxide, liquid glass, which is obtained by further dissolution of sodium silicate, contains a large amount of insoluble residue unacceptable by any standards, which, in principle, could be eliminated by conventional filtration, but, apparently, this method has not found practical application for reasons of production safety [15].

The group of liquid glasses – alkaline silicate solutions is very extensive. The silicate systems included in this group are classified according to the following criteria.

According to the degree of polymerization (l) of silica – the average number of silicon atoms that form a continuous system of siloxane bonds $\equiv Si - O - Si \equiv$ during polymerization. During the polymerization of silica, its molecular weight (M) increases, and at high degrees of polymerization, an increase in the size (d) of colloidal silica particles occurs. At a certain degree of polymerization (l), colloidal silica appears in alkaline silicate systems both in the form of a sol and in the form of highly dispersed hydrated silica (table 1).

According to the chemical composition, as the alkalinity increases, characterized by the molar ratio $\mathrm{SiO_2/M_2O}$ (the silicate module of the n system), alkaline silicate systems form a series corresponding to the four above forms of silica (table 2).

By monitoring the cation of liquid glasses, potassium, sodium, lithium and silicates of industrial enterprises are monitored. Mixed liquid glasses within four groups have also been synthesized.

Table 1. Degrees of polymerization of silica silicate solutions.

Monomers	$\to$	Lower oligomers	$\to$	Higher oligomers	$\to$	Colloidal silica, sols
$(l = 1)$		$(l = 1 \div 25)$		(polysilicic acids, $M < 10^5$)		$(M > 10^5$ or, $d > 2nm)$

Table 2. Rows with increasing alkalinity of silicate solutions.

High alkaline systems	$\to$	Liquid glasses	$\to$	Polysilicates	$\to$	Sols
$(n < 2)$		$(n = 2 \div 4)$		$(n = 4 \div 25)$		$(n > 2)$

The biggest disadvantage of this method is that, firstly, very toxic hydrochloric acid vapors with high temperature require expensive hardware for their cooling and dissolution in water, and secondly, the production of hydrochloric acid requires licensing [13].

Sulfate method. There are quite large deposits of sodium sulfate in Kazakhstan, which are currently not in demand by anyone.

The sulfate method for producing soluble glass is based on the interaction at high temperatures (1300-1500°C) of sodium sulfate with silica in the presence of a reducing agent (most often charcoal) [14].

In general, the process of formation of sodium silicate can be expressed by the equation:

$$4Na_2SO_4 + 2C + 4SiO_2 = 4Na_2SiO_3 + 4SO_2 + 2CO_2. \tag{4}$$

The reaction between Na_2SO_4 and silica, even with a significant increase in temperature, proceeds slowly and quantitative completion of it is almost impossible.

In order to accelerate the reaction, it is necessary to add a reducing agent to the charge to convert Na_2SO_4 to Na_2SO_3, which reacts with silica.

The reducing agent can be various organic substances containing carbon: sawdust, charcoal, resins, coal pitch, etc. Sawdust and charcoal are low-ash. This allows them to be widely used in the production of soluble glass.

The reducing agent, burning inside the melt, attaches oxygen contained in Na_2SO_4, as a result of which the latter passes into sodium sulfite Na_2SO_3.

Coal is added to the charge in an amount of 3-7% by weight. The amount of reducing agent introduced into the charge significantly affects the properties of the resulting soluble silicate.

With an insufficient amount of reducing agent, Na_2SO_4 remains in the melt, which does not mix with sodium disilicate and silica, which is in excess against the formula Na_2SiO_3 and $Na_2Si_2O_5$, and causes the alloy to delaminate.

With an excess of carbon in the melt, sodium sulfide Na_2S is obtained, which forms iron sulfide FeS when interacting with iron oxides, staining the soluble glass in dark colors [16].

Since, for cost reasons, this method, subject to obtaining a license for subsurface use, turns out to be the most attractive, we have studied this method more closely with the involvement of OOO "Research Institute Stromcomposite" Krasnoyarsk, Russia.

The sulfate method proposed by Krasnoyarsk NIIstromproekt, as well as the method of salt distillation described above, allows to obtain a silicate block with a low cost due to the use of a number of heat-saving aggregates [17].

Thus, it is the sulfate method with the condition of using energy-saving solutions that could become the way that would ensure the cost of the silicate block at a given level, but it has a number of significant drawbacks:

- Formation of sulfur dioxide, which requires neutralization and, accordingly, additional capital costs [11];

- As well as in the carbonate method, this one provides for the construction of an expensive glass furnace; which, in the absence of natural gas (Karaganda), also requires additional capital costs for the production of generator gas from coal.

Melting of cullet. The difference between construction or bottle glass and silicate blocks is only that the amount of soda in the raw charge in the latter case is 15% more [18].

Currently, cullet in the Republic of Kazakhstan is formed not only in window shops, but also in numerous service stations for the replacement of automobile windows. The currently unclaimed secondary glass container market is added to this volume.

In Karaganda, the service for collecting glass from window shops with delivery to the intended place of consumption is 3,000 tenge per ton. Here it is required to add 15% soda ash or sodium sulfate, i.e. the cost of raw materials in this case will be no more than 18,000 tenge per 1 ton. Processing processes (crushing and sorting), wage costs and other overhead costs will amount to about 3,000 tenge per ton. Thus, excluding energy costs, the total cost will be 21,000 tenge per 1 ton of silicate blocks. Such preliminary calculations make the processing of cullet along with sodium sulfate one of the likely ways to solve the engineering and economic task.

Study of potential sources of raw materials. Sodium silicate, produced in the form of a silicate block by Russian enterprises, is currently imported to the Republic of Kazakhstan, where it is dissolved in water and further used at enterprises of the construction, corrugated cardboard and, mainly, metallurgical industry. The most tonnage direction for the sale of sodium silicate could be the sector of production of polymer cements and concretes. The main problem in the production of annealed, clinker-free binders obtained from the waste of steelmaking enterprises (granulated blast furnace slag) is the lack of inexpensive primary or secondary alkaline materials on the market that can not only activate such binders, but also match the low price of traditional Portland cement [19].

Melting a sodium silicate block requires silicon dioxide and a suitable source of sodium.

Silicate raw materials can be man-made sources, such as cullet and microsilicon, as well as natural quartz sand [20].

Natural inexpensive sources of raw materials can be natural soda and sodium sulfate. Unfortunately, there are no technogenic alkaline sources in Kazakhstan in practically applicable volumes.

The experience of the silicate-block workshop in the Soviet period, which worked in Balkhash on the territory of the copper smelter, showed that the use of sodosulfate waste from the Pavlodar aluminum plant allowed to obtain high-quality silicate-block with a very low cost. However, along the way, an unacceptably high level of sulfur dioxide emissions was formed, which seemed insignificant “under the cover” of the main production of the combine, which also emits a huge amount of sulfur dioxide. The sodosulfate mixture is an excellent and cheap raw material for melting silicate blocks (if the furnaces are equipped with equipment for neutralizing sulfur dioxide), but the Pavlodar aluminum plant has changed the technology and does not currently ship the sodosulfate mixture.

Another inexpensive source, besides the soda-sulfate mixture, could be a deposit of natural soda. As it is known in the USA, it is due to the use of natural garden raw materials that the bulk of silicate blocks is produced.

Natural, and therefore inexpensive, soda raw materials in Kazakhstan in the explored deposits are available in negligible quantities. For example, a deposit with reserves of less than 500 tons is known in the Almaty region.

In the Altai Krai, water from Lake Tanatar with a soda content of about 5% is pumped into sedimentary basins, in which, when the temperature drops, soda precipitates, and the water drains back into the lake. There is no soda drying at the enterprise. Therefore, in addition to the natural humidity of 17%, each soda molecule contains 10 more molecules of chemically bound water.

Moreover, production was suspended after a single buyer from Stepnogorsk stopped acquiring it, after which the Altai Soda company went bankrupt. Currently, it is not possible to purchase soda from this source. It should be noted that even before the bankruptcy, the price at the level of 60 USD per 1 ton at the Kulunda station was unacceptable due to the high-water content (both chemically bound and free moisture). It turned out that 60-70% of water had to be transported, not soda. Thus, this source of raw materials for use in the production of slag-alkali cement was also unacceptable.

As a result, we came to the conclusion that cullet is currently the most suitable as the main source of raw materials, which is not only a source of silicate, but also sodium raw materials.

During the study, we found that the waste landfill of the city of Karaganda is ready to supply 200 tons of cullet every month. And together with the city of Astana and other cities of Central Kazakhstan, the total volume of available cullet is estimated at around 1000 tons per month. Other sources are workshops for the production of windows and replacement of car windows. The films inside the triplex are a harmful impurity, they are coked during melting, giving a dark color, but for a silicate block that will be used in the production of slag-alkaline cement, this is permissible.

3. Results and discussion

The main elements of modern furnaces that allow saving energy are various heat exchangers that usefully use secondary heat. In glass furnaces, fuel gases can be used to warm up incoming raw materials.

In the technological scheme proposed by OOO "Research Institute Stromcomposite" Krasnoyarsk, Russia, fuel gases are also used to produce charcoal used in the sulfate method: Sodium sulfate Na_2SO_4 (0.91 t/h), burnt molding earth (1.46 t/h) and charcoal (0.56 t/h) are fed into the melting furnace.

The components are pre-crushed and homogenized in a rod mixer.

Melting is carried out due to the combustion products of the generator gas coming from the gas generator, in which the working medium is charcoal. With an average coal consumption of 0.42 t/h in the gas generator, 2800 kg/h (2240 nm^3/h) of gengas is formed. The combustion of this amount of gengas with the supply of 2700 kg/h (2100 nm^3/h) of blast air into the combustion chamber produces 5500 kg/h of combustion products with a temperature of approximately 1550°C and a heat content of 2.9 Gcal/h.

At the outlet of the melting furnace, the temperature of the combustion products decreases to 9000°C with a residual heat content of about 1.5 Gcal/h. The total mass of the combustion products reaches approximately 6100 kg/h due to the addition of the products of the silicate block formation reaction: CO and SO_2. The amount of the first is approximately 0.18 t/h, the second is 0.42 t/h.

The combustion products are subjected to oxidative afterburning, for which 600 kg/h (465 nm^3/h) air is supplied to the afterburning chamber. As a result of afterburning, the amount of combustion products increases to 6700 kg/h, its heat content increases to 1.9 Gcal/h, and the temperature increases to 1000°C.

These combustion products are sent to retorts for dry distillation of wood waste. The retort capacity is 1 t/h of charcoal. If the initial moisture content of wood waste is 40%, then the required amount of wood waste is 5.5 t/h.

As a result of dry distillation, the heat content of combustion products drawn through the wood layer increases due to exothermic reactions of wood decay by 0.8 Gcal, however, approximately 0.3 Gcal/h is lost to the environment, and, with the charcoal leaving the retort [21].

Thus, the total heat content of combustion products at the outlet of the retort reaches 2.4 Gcal/h, and their mass increases to 11200 kg/h due to the addition of 4.5 t/h of volatile decay products. The temperature of the combustion products at the outlet of the retort will be approximately 650°C.

Volatile wood decay products contain: CO, acids, alcohols, ketones, light hydrocarbons, resin vapors, free hydrogen, therefore they must be subjected to afterburning. In 4.5 t/h of volatile, combustible compounds 1200 kg, the rest is physical and pyrogenetic water, CO_2, N. With an average calorific value of a mixture of combustible compounds 4500 kcal/kg, afterburning of volatile compounds taking into account losses allows you to get an additional 5.4 Gcal/h. For afterburning, blowing air is used in an amount of 2500 kg/h.

Thus, 13700 kg/h of combustion products with a heat content of 7.8 Gcal/h come out of the afterburning chamber.

The combustion products are sent to the heat recovery boiler G 400-PE-1 for the production of 10 t/h of steam with parameters: $T_p = 260$°C, R_p=14 atm.

Of the 10 t/h of steam, 3.7 t/h is spent on the production of electrical energy in the block electric turbine generators TGV-500M, the remainder is used for technological needs.

The process of hardening of liquid glass is accompanied by the manifestation of adhesion properties to the quartz sand filler and is carried out with natural (in air) or artificial (heating, blowing warm air) drying of the mixture. In contrast to the manufacture of casting molds, in this process it is necessary to avoid the destruction of the liquid glass base in order not to further reduce its solubility in water.

In addition, to achieve high strength, first of all, it is necessary to achieve the most dense packing of sand grains, which, in addition to molding pressure, requires a certain grain size distribution and optimal viscosity of liquid glass. In this case, the dependence of strength on the glass content in the system passes through a sharp maximum. This dependence is shown in figure 2.

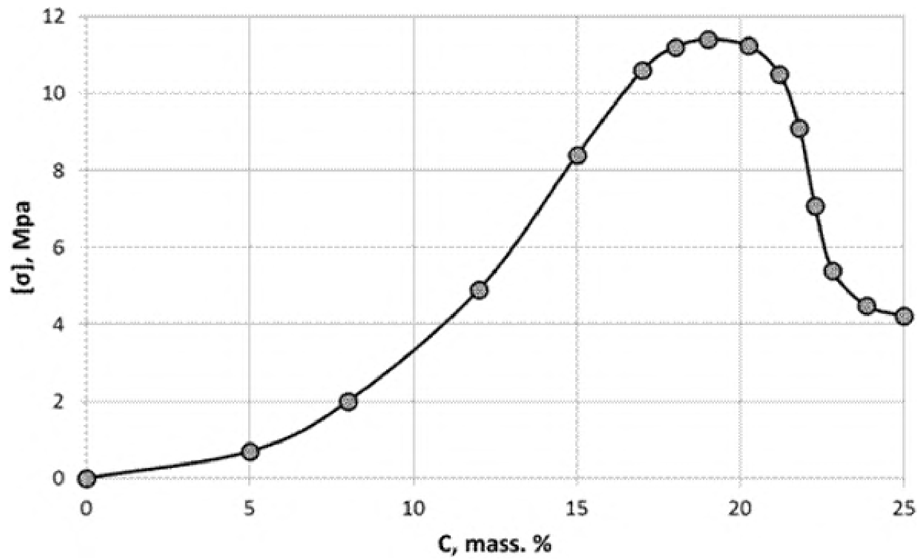

Figure 2. Dependence of the tensile strength on the content of liquid glass.

After the recovery boiler, the combustion products are neutralized in a "wet" scrubber [22].

The high cost of glass-melting furnaces of the bath type, which are used in glass factories with a capacity of 40-60 tons per day, is estimated at 2-3 million US dollars. This goes beyond the boundary conditions. Sodium silicate is a key source of reactive silica, which is in high demand in many industries including detergents, rubber, food and beverages, and paper and pulp. The global sodium silicate market was valued at USD 6.3 billion in 2018, growing at a CAGR of 3.2% during the forecast period 2020-2026 figure 3.

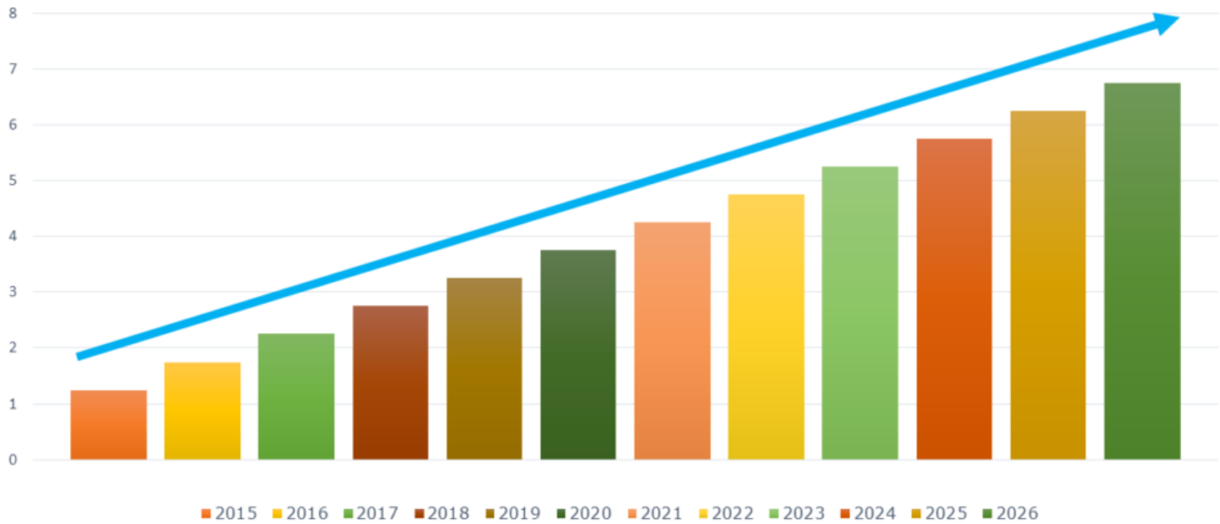

Figure 3. Global market forecast according to [23].

The growing demand for other derivatives such as silica gels and silica sols in applications including paints and coatings, plastics and inks is expected to have a positive impact on market growth during the forecast period. Another promising melting method would be glass melting in a cyclone furnace [18].

Scientists of the Academy of Sciences of the Kazakh SSR were seriously engaged in this topic in the 70s of the 20th centuries and were among the world leaders. Such an experimental furnace was even used for melting copper raw materials at the Balkhash copper Smelting plant.

Cyclone furnaces consume 1.5-1.6 times less fuel than rotary furnaces, and have a cost 10-20 times less in terms of capital costs for their construction [10].

It turned out that cyclone furnaces are currently used to produce mineral and glass wool in Germany.

The main disadvantage of melting raw materials in a cyclone is the huge volume of fuel gases that require purification. The fact is that in cyclone furnaces, the charge in a pulverized state with speeds of several hundred km/h is blown into the cyclone together with fuel gases. Some of the raw materials are melted, but some come out of the cyclone, which leads to a loss of raw materials up to 15%. At the same time, there is a technical problem of cooling the flow of the outgoing gas and its purification from solid impurities. Such a task is quite feasible, but in the given parameters of the task it will require the construction of a battery of heat-resistant cyclones, the cost of which is higher than the cost of the furnace itself.

Therefore, our research should be in the field of energy saving of electric direct-heated glass furnaces. The design of such furnaces is simple, requires little space and capital costs. The only drawback of such furnaces is the high-power consumption – 1000 kw-hours of electricity is required for 1 ton of silicate blocks, which at current prices is 16,000 tenge per ton of silicate blocks.

As part of the task, it is required to reduce the electricity consumption to 7000-8000 tenge per ton of silicate blocks. In the course of the conducted scientific and technical search, it turned out that currently there are technologies that can reduce consumption costs by 2 or even more times.

The main component is an electric direct heating furnace. The efficiency of such furnaces is many times higher than the efficiency of gas furnaces, since in our case the heat flow is carried out from below (bottom electrodes), and not from above, as in the case of coal or gas furnaces, where the torch heats the mass from above, which is why it is necessary to build an expensive vault. But in our case, the electric furnace is additionally equipped with a reactive energy compensation unit with a magnetic amplifier, as a result of which electricity is saved at least 2 times.

The authors are engaged in the introduction into practice of a highly efficient resource-saving process for the production of sodium silicate from cullet with the use of innovative electric melting technology, which allows a multiple reduction in energy costs and the use of energy-saving technology for obtaining an aqueous solution of sodium silicate using a highly efficient apparatus protected by a patent.

The introduction of the proposed technology will allow not only to start a solution for import substitution, but also to indicate a technical solution for involving tens of millions of tons of Temirtau and Taraz slag into economic turnover, which will reduce carbon dioxide emissions by reducing the production of Portland cement, which currently produces carbon dioxide in rotating coal furnaces almost more than cement itself.

In addition, it is planned to obtain sodium silicate not from quartz raw materials and soda, but from secondary glass and soda, since there is already a high amount of sodium oxide required in the cullet. Another difference of the proposed technology is the use for electric melting of a furnace equipped with a reactive power compensation unit with a magnetic amplifier, which will make it possible to reduce the specific amount of electricity by at least 2 times.

The second technical difference is the technology of dissolution of sodium silicate. Traditionally, sodium silicate is dissolved in water in autoclaves at high vapor pressure, which is too energy-consuming. In our case, the silicate block is crushed and dissolved in water at a temperature of 95-98 degrees Celsius at normal pressure. At the same time, an energy-efficient device is used, protected by patent No.2397 with the authorship of one of the team members – T. S. Dauletbakov [24].

The traditional technology of melting sodium silicate involves melting quartz sand and soda in bathroom furnaces. This technology, firstly, requires high capital investments for the construction of a bathroom furnace, and secondly, requires the presence of a source of natural gas or where there is none, as in our case, a gas generator set for the production of generator gas from coal, which also increases the cost of the project [11].

The technology of dissolving quartz sand in caustic soda solution is also known, which sharply increases the cost of products due to the high cost of NaOH (caustic soda). The technology of obtaining sodium silicate from cullet with the addition of 8-15% soda ash (Na_2CO_3) is also used with melting in bathroom furnaces and is the closest to this project.

We propose the production of sodium silicate from cullet with soda and / or sodium sulfate, but, characterized in that:

- Melting is carried out not in an expensive bath-type gas furnace, but in a compact electric furnace of direct heating;
- The electric furnace is equipped with a reactive power compensation unit with a magnetic amplifier, which gives a multiple reduction in electricity consumption of at least 2 times;
- The components of the charge are mechanically activated in a roller mill before melting.

This leads to a partial reaction of the formation of sodium silicate already in the mill and further to a multiple reduction in energy costs during melting in the furnace at least 1.5 times more.

At the stage of dissolution of the silicate block in water, an autoclave-free technology is provided, in which the finely ground silicate block is dissolved in water at normal pressure, which reduces energy consumption compared to the traditional technology of dissolution in superheated steam at high pressures.

The cost of water vaporization is 2260 kJ/kg, so the specific heat required for heating water from 0 to 98 degrees Celsius is only $4.1 \times 98 = 401$ kJ/kg.

That is, the amount of energy required for water vaporization, taking into account that the steam still needs to be heated to 150 degrees with traditional technology compared to the proposed 6 times more.

The main problem in the production of sodium silicate is high capital intensity and high energy intensity.

The authors are working in the field of reducing energy costs. For this purpose, the technology of reactive power compensation with a magnetic amplifier is proposed, which is key, can be used in hundreds and thousands of companies only in Kazakhstan, where there are significant unit costs for electricity – from mining to street lighting.

In a broad sense, reactive power compensation technology with a magnetic amplifier can be used not only for melting sodium silicates, but also in metallurgical furnaces, mining farms, electrolysis workshops, and municipal lighting. The technology of reactive power compensation with a magnetic amplifier is currently tested and used in Turanga LLP (Almaty) in industrial conditions at a wood thermating plant with a capacity of 150 kW. It is planned to apply the same technology in the melting of sodium silicate in an electric furnace with a capacity of 1MW.

4. Conclusions

The most likely to be used under the conditions of the task is the processing of natural sodium sulfate. However, in terms of availability, this type of raw material, despite its widespread distribution in Kazakhstan, is not suitable for solving this problem, since no one has the rights to extract it.

Therefore, the processing of recycled glass, now unclaimed by the domestic industry, can be a source of raw materials for the production of silicate blocks with a given cost at the level of 28-30 thousand tenge per ton.

The engineering and technical embodiment of melting can be cyclone melting, provided that the issue of waste gas purification is resolved, as well as melting in electric furnaces, provided that energy savings are ensured.

Sodium silicate, produced in the form of a silicate block by Russian enterprises, is currently imported to the Republic of Kazakhstan, where it is dissolved in water and further used at enterprises of the construction, corrugated cardboard and, mainly, metallurgical industry.

The most tonnage direction for the sale of sodium silicate could be the sector of production of polymer cements and concretes. The main problem in the production of non-roasting, non-clinker binders obtained on the basis of waste from steelmaking enterprises (granulated blast furnace slag) is the lack of inexpensive primary or secondary alkaline materials on the market that can not only activate such binders, but also match the low price of traditional Portland cement.

Thus, the introduction of the proposed technology will allow not only to start a solution for import substitution, but also to indicate a technical solution for involving tens of millions of tons of Temirtau and Taraz slag into economic turnover, which will reduce carbon dioxide emissions by reducing the production of Portland cement, which currently produces almost more carbon dioxide in rotating coal furnaces, than the cement itself.

In addition, the project provides for the production of sodium silicate not from quartz raw materials and soda, but from secondary glass and soda, since there is already a high amount of required sodium oxide in the cullet.

Another difference between the project and the traditional ones is the use of an electric furnace equipped with a reactive power compensation unit with a magnetic amplifier, which will make it possible to reduce the specific amount of electricity by at least 2 times.

The second technical difference is the technology of dissolution of sodium silicate. Traditionally, sodium silicate is dissolved in water in autoclaves at high vapor pressure, which is too energy-consuming. In our case, the silicate block is crushed and dissolved in water at a temperature of 95-98 degrees Celsius at normal pressure. At the same time, an energy-efficient device is used, protected by patent No. 2397 with the authorship of one of the team members – T. S. Dauletbakov.

But the most important consequence of the project is the practical expansion of reactive power compensation technology with a magnetic amplifier, which in the future can be used in all power grids with a significant reduction in energy consumption and ultimately significantly affect the decarbonization of the industry of the Republic of Kazakhstan.

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References
[1] Pysmennyi S, Fedko M, Shvaher N and Chukharev S 2020 *E3S Web of Conferences* **201** 01022 URL https://doi.org/10.1051/e3sconf/202020101022
[2] Pysmennyi S, Fedko M, Chukharev S, Rysbekov K, Kyelgyenbai K and Anastasov D 2022 *IOP Conference Series: Earth and Environmental Science* **970**(1) 012040 URL https://doi.org/10.1088/1755-1315/970/1/012040
[3] Pysmennyi S, Peremetchyk A, Chukharev S, Fedorenko S, Anastasov D and Tomiczek K 2022 *IOP Conference Series: Earth and Environmental Science* **1049**(1) 012029 URL https://doi.org/10.1088/1755-1315/1049/1/012029
[4] Baskanbayeva D D, Krupnik L A, Yelemessov K K, Bortebayev S A and Igbayeva A E 2020 *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu* (5) 68–74 URL https://doi.org/10.33271/NVNGU/2020-5/068
[5] Yelemessov K, Nauryzbayeva D, Bortebayev S, Baskanbayeva D and Chubenko V 2021 *E3S Web of Conference* **280** 070074 URL https://doi.org/10.1051/e3sconf/202128007007
[6] Pysmennyi S, Chukharev S, Khavalbolot K, Bondar I and Ijilmaa J 2021 *E3S Web of Conferences* **280** 08013 URL https://doi.org/10.1051/e3sconf/202128008013
[7] Kyelgyenbai K, Pysmennyi S, Chukharev S, Purev B and Jambaa I 2021 *E3S Web of Conferences* **280** 08001 URL https://doi.org/10.1051/e3sconf/202128008001
[8] Pysmennyi S, Chukharev S, Kyelgyenbai K, Mutambo V and Matsui A 2022 *IOP Conference Series: Earth and Environmental Science* **1049**(1) 012008 URL https://doi.org/10.1088/1755-1315/1049/1/012008
[9] Lothenbach B, Kulik D A, Matschei T, Balonis M, Baquerizo L, Dilnesa B, Miron G D and Myers R J 2019 *Cement and Concrete Research* **115** 472–506 ISSN 0008-8846 URL https://doi.org/10.1016/j.cemconres.2018.04.018
[10] Kruglyak S L and Yakovina A P 1991 *Cement* 71–73
[11] Korneev V I and Danilov V V 1996 *Liquid and soluble glass* (St. Petersburg: Stroyizdat)
[12] Galperina M K and Tarantul N P 1989 *Tr. NIIstroykeramika* **65** 10–26
[13] Fishman I R 1989 *Technology, economics, organization of production and management* **37**(8) 40
[14] Gaidzhurov P P, Tkachev A G and Tamazov M V 1999 *Glass and Ceramics* **56**(9) 275–278 ISSN 1573-8515 URL https://doi.org/10.1007/BF02681374
[15] Owoeye S S, Abegunde S M and Oji B 2021 *Chemistry and Materials Research* **13**(1) 66–75 URL https://doi.org/10.7176/CMR/13-1-03

[16] Toturbiyev B D 1988 *Stroitel'nyye materialy na osnove silikat-natriyevykh kompozitsiy* (Moskva: Stroyizdat)
[17] Mamchenkov E A and Prokof'ev V Y 2019 *ChemChemTech* **62**(3) 89–93 URL https://doi.org/10.6060/ivkkt.20196203.5949
[18] Tanaka H, Yamada T, Sugiyama S, Shiratori H and Hino R 2005 *Journal of Colloid and Interface Science* **286**(2) 812–815 ISSN 0021-9797 URL https://doi.org/10.1016/j.jcis.2004.12.051
[19] Minko N I and Lavrov R V 2015 *Bulletin of the Belgorod State Technological University. V. G. Shukhova* (2) 172–176
[20] Minjko N I and Lavrov R V 2015 *International Research Journal* (2(33)) 23–26 URL https://research-journal.org/en/archive/2-33-2015-february/novoe-v-texnologii-silikatnogo-stekla
[21] Minko N I and Lavrov R V 2015 New in silicate glass technology
[22] Elinzol M P and Vasilkov S G 1980 *Fuel-containing industrial waste in the production of building materials* (Moskva: Stroyizdat)
[23] DataIntelo 2020 Sodium Silicate Market Share, Size | Growth Analysis Report, 2031 URL https://dataintelo.com/report/sodium-silicate-market/
[24] Dauletbakov T S 2003 *Bulletin of KazNTU* (4) 185–187

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Sustainable performance of alkali-activated blast furnace cement concrete with high freeze-thaw resistance

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Sustainable performance of alkali-activated blast furnace cement concrete with high freeze-thaw resistance

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Abstract. The application of blast furnace cements with minor clinker constituent is an actual task due to their conformity with modern tendencies of sustainable development. The alkali metal compounds were proposed to increase activity of CEM III/C. The aim of the research was to investigate the effects of technological factors on porous structure of alkali-activated blast furnace cement concrete (further, AABFC concrete) to ensure its sustainable performance by criterium of freeze-thaw resistance in NaCl solution. The effects of fresh concrete consistency, aggregate state of alkaline component and curing conditions on sustainability of AABFC concrete were investigated. Increasing of fresh concrete consistency from class S1 up to class S4 due to chemical plasticization as well as application of alkaline component in dry form, in contrast to liquid form, ensures negative changes in porous structure of AABFC concrete. These changes cause decreasing of freeze-thaw resistance from mark F500 down to F200. It was revealed that hardening of plasticized AABFC concrete under normal conditions ($t = 20 \pm 2\ ^\circ$ C, $RH = 95 \pm 5\%$), compared with hardening in water or under steam curing ($t = 85 \pm 5\ ^\circ$ C), ensures more effective porous structure which causes maintained freeze-thaw resistance of F300 in contrast to F200 and F250 agreeable.

1. Introduction

To decrease the content of clinker constituent in cements due to use of ground granulated blast furnace slag (further, GGBFS) [1], fly ash [2], limestone [3], natural zeolites [4], biochar (the carbon negative product of pyrolysis) [5], etc. is an effective way to meet the requirements of sustainable development. Besides of ecological aspect (effective consumption of raw recourses, reduction of CO_2 emission), such replacement causes diminution of prime and logistics costs, as well as provides the means to use local raw materials [6, 7]. However, these cements suffer from slow hydration kinetics, resulting in less early strength gain, which is main drawback in construction applications.

The most known ways to activate hydraulic properties of the cements containing GGBFS is to apply calcium [8] and sulfate activators [9]. It is also known that low alkaline [10], nearly neutral salts [11] as well as Na (K) salts of strong acids [12] can be used as activators as well. However, insufficient strength of blast furnace cements in accordance with [13] and the possibility to increase only early strength are disadvantages of these means [14, 15]. It was shown, that the application of oxides [16] or salts of alkaline metals (sodium aluminate [17], sodium carbonate and silicate [18]), which provide an high alkaline reaction in water, can be a solution to increase the efficiency of blast furnace cements with minor clinker constituent without decrease of strength. Thus, blast furnace cements activated by alkali metal compounds are in compliance with mandatory requirements [19].

The alkali-activated blast furnace cements (further, AABFC), obtained due to mentioned activation, are the most perspective ones to ensure advanced service life of concrete structures. To ensure the durability of constructions is one more current world tendency of sustainable development of mankind. This fact can be confirmed by numerous scientific researches concerning durability of structures which are exposed to different aggressive effects, i.e. atmospheric [20], freeze-thaw cycles [21], alkali of aggregate [22], seawater [23], high temperatures [24], fire [25,26], etc. Proposed recommendations to ensure durability of structures while use of recycled concrete [27–29].

In general cases, alkali-activated blast furnace cement concretes are characterized by advanced performances in aggressive environments such as corrosion resistance [30], sulfate resistance [31] and freeze-thaw resistance [32], including salt scaling resistance [33], in comparison with analogues based on traditional clinker cements.

It is well known that the durability of concrete structures cannot be evaluated using only one performance. The most important properties of concrete for a specified case are used for evaluation of durability depending on destination and environment [34]. Resistance of concrete to freeze-thaw cycles and sodium chloride scaling is one of the criteria. The mentioned environment can be classified as exposure class XF4 (road and bridge decks exposed to deicer agent, splash zones of marine structures, etc.) according to [35]. It is well known that NaCl is the most demanded salt among deicers [34, 36, 37] as well as the predominant one in seawater [38, 39]. The above results have been defined the choice of sodium chloride as corrosion environment to evaluate the durability of concrete to freeze-thaw resistance.

Increased freeze-thaw resistance of AABFC concrete in NaCl solution is caused by several factors, including features of hydrated phases. It is known, that interaction of sodium chloride with hydration products of Portland cement ensures destruction of concrete. Particularly, decreasing of $Ca(OH)_2$ in hydration products in consequence of leaching as well as exchange reaction with sodium chloride NaCl with formation of $CaCl_2$ leads to decreasing of basicity of highly-calcium hydrosilicates (the main hydration products of portland cement) [34, 40]. Besides, participation of sodium chloride in hydration processes of portland cement ensures transformation of monosulfate $3CaO \cdot Al_2O_3 \cdot CaSO_4 \cdot 10H_2O$ to Friedel's salt $3CaO \cdot Al_2O_3 \cdot CaCl_2 \cdot 10H_2O$ (AFm-phase) as well as to secondary ettringite $3CaO \cdot Al_2O_3 \cdot 3CaSO_4 \cdot 32H_2O$ (AFt-phase) [41,42]. Formation of secondary ettringite can cause destruction of concrete due to crystallization pressure on porous sides while volume increases. Advanced freeze-thaw resistance of AABFC concrete in solution of NaCl is caused by the absence of portlandite in hydration products [43] as well as by the absence of ettringite or due to changes in its morphology in highly-alkaline hydration medium from filamentous, needle to prismatic as well as plate shape [44].

Solution of NaCl can also provide steel reinforcement corrosion in constructions in consequence of transport of aggressive Cl^- ions in concrete [45]. AABFC concrete is characterized by increased protective properties to steel reinforcement due to high content of gel-like hydrosilicates and formation of alkaline hydroaluminosilicates (analogues of natural zeolites), which can bind Cl^- ions [43, 46, 47]. The enhancement of steel reinforcement protection in AABFC concretes, obtained from high consistency mixes, was proposed [12,18,23].

Increased freeze-thaw resistance of AABFC concrete compared with portland cement concrete is caused also by influence of alkaline component on decreasing of freezing temperature of solution in porous space [43]. It is well-known, that increasing of water volume while formation of ice by 8. . . 9 % ensures pressure on sides of pores and causes destruction of concrete [34]. However, freezing of liquid in pores occurs at temperatures below 0 $^\circ$ C because of solution in pores of stone is not pure water and contains soluble substances (alkalis, oxides and hydroxides of alkaline-earth metals, sulfates, etc.) [48]. Increased content of compounds of alkaline metals in porous solution causes increased freeze-thaw resistance of AABFC concrete compared with portland cement [43, 49].

The peculiarities of porous structure cause advanced freeze-thaw resistance of AABFC concrete. In common case, the porous structure of cement stone is presented by gel (1.5. . . 10.0 nm), capillary (0.01. . . 1.00 nm) and closed (10. . . 500 μm) pores [50]. At that, freeze-thaw resistance and accordingly durability of concrete are caused mainly by capillary porosity in contrast to strength of concrete, which depends on total porosity [34]. Capillary effect, which is caused by dependence of freeze point from the size of pores, causes the influence of porous structure on freeze-thaw resistance of concrete. Water firstly freezes in capillary pores whereas one remains in liquid form in smaller gel pores while freezing. Thermodynamic unbalanced state causes motion force for removal of water from smaller to larger pores and occurs because of the pressure under water is higher than under ice [34]. Increased gel phase while decreased volume of capillary pores compared with Portland cement [43] causes advanced freeze-thaw resistance of AABFC concrete.

Porous structure of AABFC concrete in one's turn is caused by technological factors such as consistency of fresh concrete, form (state) of alkaline component, curing conditions, etc. The modern requirements to consistency fresh concretes are governed by practice [51–55]. Consistency of fresh concrete is regulated by surfactants. Principles for choice of surfactants as the bases of complex admixtures were proposed [56, 57]. Effectiveness of complex admixture "polyorganohydrosiloxane – sodium lignosufonate – polyethylene glycol" for AABFC concrete was determined while providing both electrostatic and steric mechanism of plasticization [56]. However, increasing of consistency causes negative changes in concrete structure, which lead to increasing of porosity and consequently less freeze-thaw resistance.

The features of AABFC technology, which are caused by different aggregative state of alkaline components and chemical admixtures (dry form or liquid form), provide various intensity in formation of hydrosilicate gel and, consequently, different performances of AABFC concrete [43]. Thus, the aim of this research was to investigate the effects of technological factors on porous structure of AABFC concrete to provide its high freeze-thaw resistance in solution of sodium chloride as criterium of sustainable performance.

2. Raw materials and testing techniques

The main constituents of the blast furnace cement (CEM III/C, in accordance with EN 197-1:2011) were presented by:

- ground-granulated blast furnace slag (further, GGBFS) (% by mass: CaO – 47.30, SiO_2 – 39.00, Al_2O_3 – 5.90, Fe_2O_3 – 0.30, MgO – 5.82, SO_3 – 1.50, TiO_2– 0.31), basicity modulus= 1.11, content of glass phase= 84.0 %, specific surface= 450 m^2/kg (by Blaine);
- Portland cement CEM I 42,5 R (% by mass: CaO – 64.13, SiO_2 – 25.14, Al_2O_3 – 5.17, Fe_2O_3 – 4.12, MgO – 0.88, SO_3 – 1.27, $K_2O + Na_2O$ – 0.99).

The blast furnace cement was composed, % by mass: GGBFS – 95, Portland cement – 5.

The alkaline component (33 mass % Na_2CO_3 + 67 mass % $Na_2O \cdot SiO_2 \cdot 5H_2O$) was introduced into a concrete mixer in dry form (powder) or in liquid form (water solution, 1180 kg/m^3) in such a way that its content in the concrete (as Na_2O-equivalent) would be equivalent. The contents of alkali metal compounds (alkaline activators) were taken over 100 % of the aluminosilicate components in accordance with [19].

A river silica sand (fineness modulus 1.8) was used. A granite gravel with grain sizes between 5. . . 10 mm (fr. 5/10) and 10. . . 20 mm (fr.10/20) was used as coarse aggregate.

Reference composition of concrete was used according to [58], while application of alkaline component in dry form or in liquid form, kg/m^3: AABFC – 350, silica sand – 740, granite gravel – 330 (fr.5/10) and 780 (fr.10/20).

AABFC concrete was modified by complex admixture (CPA) with the main plasticizing effect. CPA was presented by the components:

- sodium lignosulfonate (further, LST) in accordance with CAS 8061-51-6 (pH $\geqslant$ 8.5);
- waterproofing agent based on ethyl hydro-siloxane polymer (further, WA) in accordance with CAS 63148-57-2.
- surfactant based on polyether (polyethylene glycol "PEG-400", JSC "Barva" in accordance with CAS 25322-68-3.

WA was used to intensify grinding and to prevent sorption of water from air and to retain the properties of AABFC. Contents of CPA components, % by mass of AABFC, were: LST – 1.00, WA – 0.06, polyethylene glycol – 0.50.

The AABFC components and a half of aggregates together with LST and mixing liquid (water or solution of the alkaline component) were properly mixed in mixer for 1 min, then the remaining part of aggregates was added and mixed together for the next 2 min.

Consistency (workability) was determined by cone slump according to the national standard of Ukraine [59].

The prepared concrete mixtures were placed into moulds and compacted under vibration at a vibrating table, then covered with a plastic film and placed into a chamber for hardening under normal conditions (t = 18±2 ° C and RH = 95±5 %), where it was stored for 2 days until demoulding. A part of the specimens after taken from the moulds was placed for further hardening in water, the other part was left for hardening under normal conditions, and some specimens were steam cured at t = 85±5 ° C.

Water absorption and porosity of the AABFC concrete were tested in accordance to national standard of Ukraine [60]. The concrete cubes (100 mm) after 28 days of hardening were dried up to a constant weight at t = 105±10 ° C. Then, the specimens were saturated with water until a constant weight would be obtained at t= 20±2 ° C. The values of porosity were calculated from the values of average density and water absorption.

Freeze-thaw resistance of AABFC concrete (figure 1) was studied according to the third test method prescribed by the national standard of Ukraine [61]. According to this accelerated method, the concrete cubes (100 mm) were saturated with a 5 % solution of NaCl at t= 18±2 ° C and after that were subjected to freezing at t = -50 ° C. Thawing was done in a 5 % solution of NaCl. A class of concrete in freeze-thaw resistance was designated as a number of alternate freezing and thawing at which a mean compressive strength decreased by no more than 5 %. The freeze-thaw resistance of concrete was assessed by the correspondence between permissible number of freezing-thawing cycles by the mentioned method and by the first (basic) method prescribed in mentioned standard.

3. Results and discussions

The effects of fresh concrete consistency, aggregate state of alkaline component and curing conditions as technological factors on porous structure of AABFC concrete were investigated to ensure its sustainability.

3.1. Effects of fresh concrete consistency and aggregate state of alkaline component

The porous structure and corresponding values of freeze-thaw resistance of AABFC concrete were compared. AABFC concrete was obtained with different consistency (table 1, figure 2, figure 3, figure 4): class S1 (reference) and class S4 (plasticized by CPA). It was revealed, that consistency of fresh concrete is important factor of porous structure. Thus, increasing of

Figure 1. A freezing chamber for testing freeze-thaw resistance.

Table 1. The porous structure and freeze-thaw resistance of alkali-activated blast furnace cement concrete versus form of alkaline component and consistency.

Strength class of concrete	W/C (S/C)	Consis-tency, cm	Water absorption Wm, %	Changes in mass, %	Changes in strength, %	Freeze-thaw resistance
			Dry form of alkaline component			
B35	0.36	18	3.39	+1.05	-9.0	F200
B40	0.34	2	3.12	+0.8	+0.5	F400
			Liquid form of alkaline component			
B35	0.34	20	3.70	+0.04	-1.0	F300
B40	0.32	3	2.88	+0.19	-5.7	F500

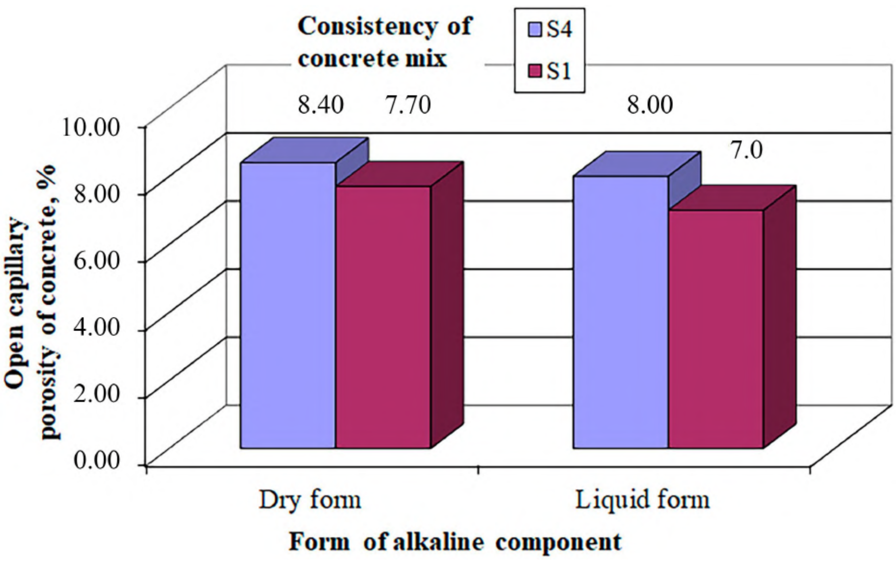
Note. The specimens hardened in water

consistency from class S1 up to class S4 while application of alkaline component in dry form ensured deterioration of porous structure, i.e. increasing of volume of open capillary pores by 9.1 % (figure 2a) and decreasing volume of conditionally closed pores by 41.2 % (figure 2b). Less volume of conditionally closed pores determined formation of minor dense and more permeable structure, which caused deterioration of physical and mechanical properties of AABFC concrete, including freeze-thaw resistance decrease from mark F400 down to mark F200 (figure 3a). Application of alkaline component in liquid form provided the similar dependence. Changes in consistency from class S1 up to class S4 ensured increasing volume of open capillary pores by 14.3 % (figure 2a) and corresponding decreasing of conditionally closed pores by 20.7 % (figure 2b), that was factor of reduction of freeze-thaw resistance from mark F500 down to mark F300 (figure 3b).

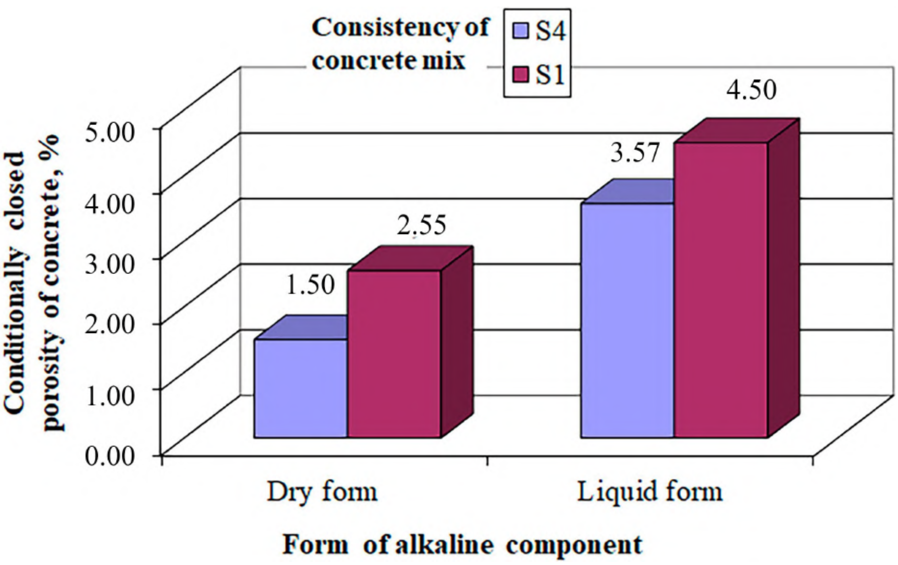
Specified changes in porous structure and freeze-thaw resistance of AABFC concrete was caused by increasing values of water/cement ratio (W/C) from 0.34 up to 0.36 or solution/cement ratio (S/C) from 0.32 up to 0.34 while application of alkaline component in dry form or liquid form agreeably. Less freeze-thaw resistance of AABFC concrete was also caused by increased air-entraining due to CPA. That is explained by decreasing of surface tension between water and air [62].

Thus, increasing consistency caused negative effect on freeze-thaw resistance of AABFC concrete that is in dissonance with the modern requirements to high consistency of fresh concrete.

Application of alkaline component in dry form, in contrast to liquid form, ensured higher volume of open capillary pores by 5.0 % and 10.0 % at consistency classes S1 and S4 agreeably.



(*a*)



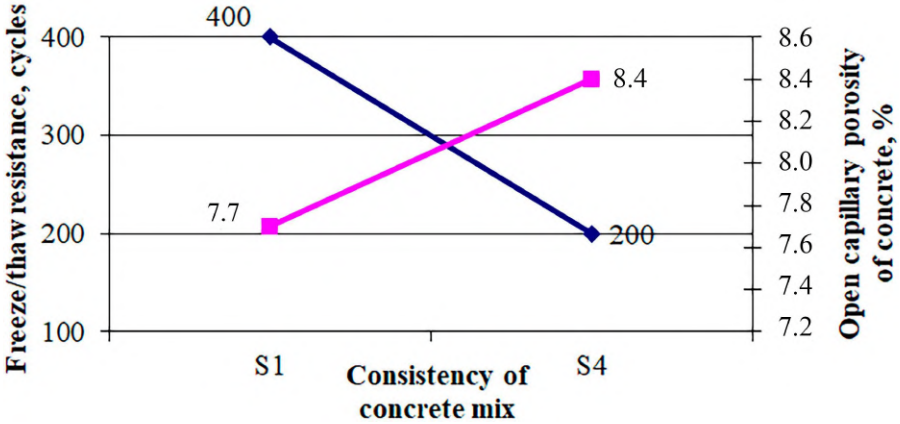
(*b*)

Figure 2. The influence of consistency and form of alkaline component on the volumes of open capillary pores (*a*) and conditionally closed pores (*b*) of alkali-activated blast furnace cement concrete.

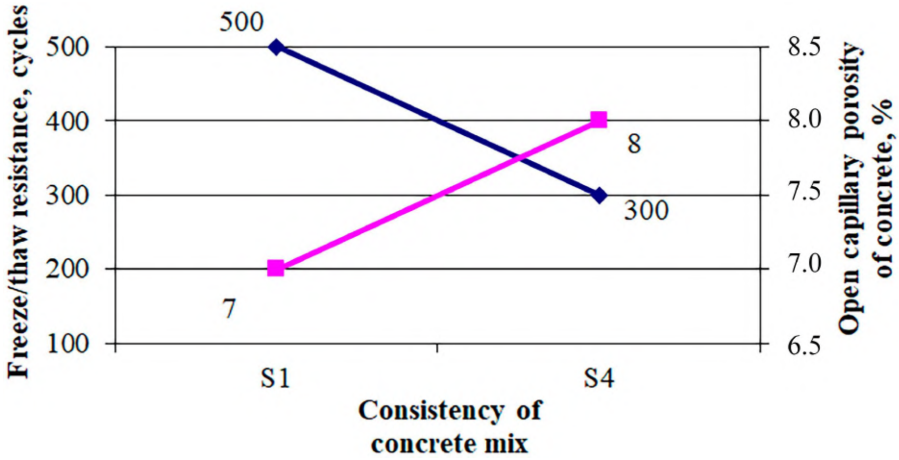
Lack in filling intensity of porous space by hydrosilicate gel caused this phenomenon (figure 2a).

Decreasing volume of conditionally closed pores by 58.0 % and 43.3 % consequently occurred (figure 2b). Specified changes in porous structure ensured decreasing tendency in freeze-thaw resistance of AABFC concrete from F500 down to F400 (figure 4a) as well as from F300 down to F200 (figure 4b).

Obtained regularities confirm expediency of alkaline component exactly in the liquid form, that is on contrary to modern requirements concerning production of AABFC's namely under "all-in-one" technology.



(*a*)



(*b*)

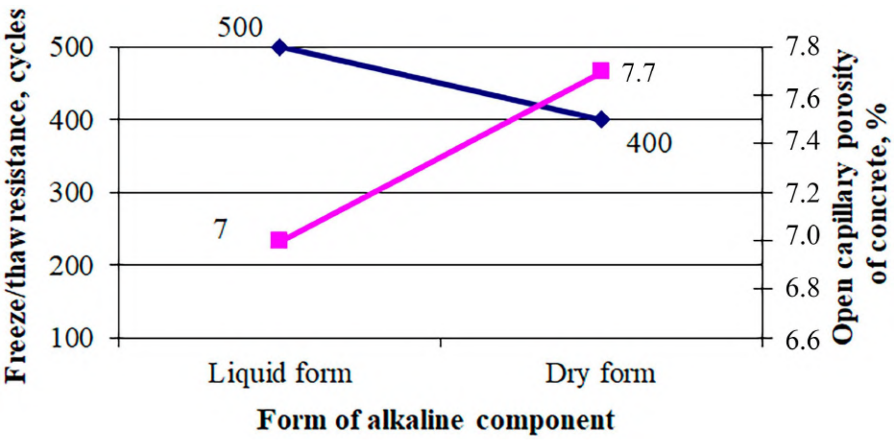
Figure 3. Open capillary porosity and freeze-thaw resistance of alkali-activated blast furnace cement concrete vs. form of alkaline component: dry form (*a*), liquid from (*b*).

3.2. Effect of curing conditions
Normal curing conditions of AABFC concrete was more advisable if compared with curing in water or under steam curing in the view of formation of effective porous structure (table 2).

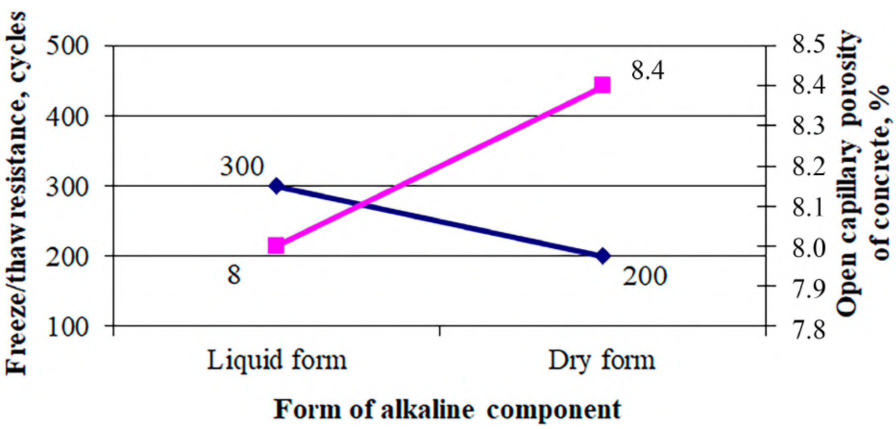
Porous structure of plasticized AABFC concrete, at consistency of class S4 and after hardening during 28 d under normal conditions, was characterized by decreased volume of open capillary pores by 5.0 % and 1.3 % as well as by increased volume of conditionally closed pores by 35.7 % and 20.0 % compared with analogues under water or steam curing (figure 5). Specified changes in porous structure contributed to formation of AABFC concrete with more dense and impermeable structure, which is able for self-healing. This phenomenon provided advanced freeze-thaw resistance mark F300 in contrast to marks F200 and F250 of analogues (figure 6).

Thus, effective technological decisions to ensure advanced freeze-thaw resistance of AASC concrete in solution of sodium chloride as criterium of its sustainability were determined.

4. Conclusion
1. The activization of blast furnace cement by alkali metal compounds although taking into account the influence of technological factors on porous structure of concrete can provide



(a)



(b)

Figure 4. Open capillary porosity and freeze-thaw resistance of the alkali-activated blast furnace cement concrete vs. consistency: class S1 (a), class S4 (b).

Table 2. The porous structure and freeze-thaw resistance of alkali-activated blast furnace cement concrete versus curing conditions.

Curing conditions	Strength class of concrete	W/C	Consis-tency, cm	Water absorption Wm, %	Changes in mass, %	Changes in strength, %	Freeze-thaw resistance
			Dry form of alkaline component				
Water	B35	0.36	18	4.0	-0.12	-1.68	F200
Steam curing	B35	0.36	19	4.2	+0.16	+1.85	F250
Normal conditions	B35	0.36	19	4.1	+0.12	+4.608	F300

its sustainable performance by criterium of advanced freeze-thaw resistance in solution of sodium chloride. Fresh concrete consistency, aggregate state of alkaline component and

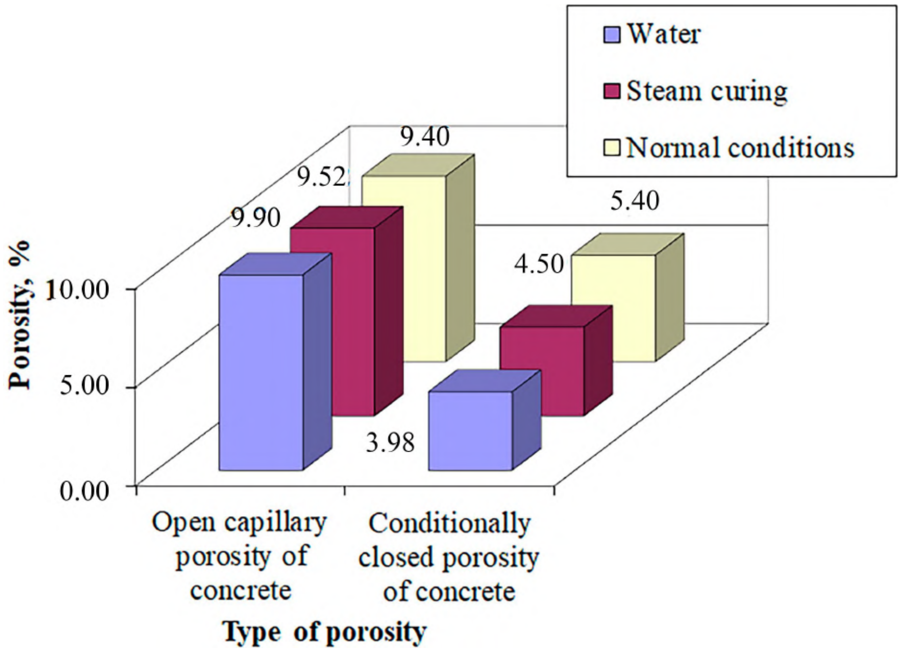


Figure 5. Porous structure of alkali-activated blast furnace cement concrete vs. curing conditions.

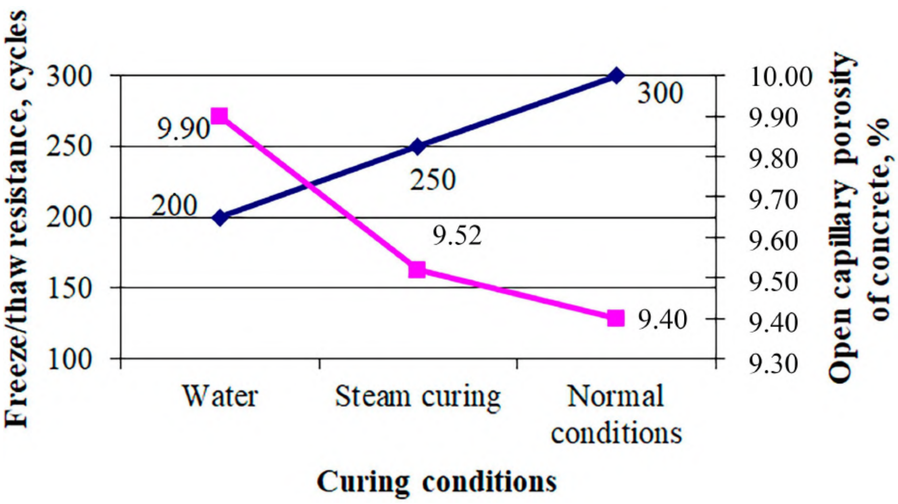


Figure 6. The volume of open capillary pores and freeze-thaw resistance of alkali-activated blast furnace cement concrete vs. curing conditions.

curing conditions are considered as appropriate technological factors to handle the structure of alkali-activated blast furnace cement concrete under the exposure class XF4.

2. It was shown, that increasing of fresh concrete consistency from class S1 up to class S4 by means of chemical modification as well as application of alkaline component in dry form caused less freeze-thaw resistance of alkali-activated blast furnace cement concrete in solution of NaCl as a result of negative changes in porous structure. Thus, application of complex admixture “polyorganosiloxane – sodium lignosulfonate – polyethylene glycol” while use of alkaline component in dry form ensured increasing open capillary porosity by

20 % and decreasing of conditionally closed porosity by 67 % that was accompanied by diminution of freeze-thaw resistance the concrete by 60 %.

3. It was revealed, that negative effect of plasticization can be compensated while dry form of alkaline component and sustainable performance of alkali-activated blast furnace cement concrete can be ensured due to hardening under appropriate temperature-humidity conditions. In that way, freeze-thaw resistance of the plasticized concrete while hardening in normal conditions, in contrast to hardening in water or under steam curing, increased up to 1.3…1.5 times in consequence of reduced open capillary porosity by 5.0 % and increased volume of conditionally closed pores by 36.0 %.

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References

[1] Kostyuk T, Vinnichenko V, Plugin A, Borziak O and Iefimenko A 2021 *IOP Conference Series: Materials Science and Engineering* **1021**(1) 012016 URL https://doi.org/10.1088/1757-899X/1021/1/012016
[2] Sanytsky M, Kropyvnytska T, Kotiv R, Bevz M and Fic S 2021 *E3S Web of Conferences* **280** 07002 URL https://doi.org/10.1051/e3sconf/202128007002
[3] Bentz D P, Ferraris C F, Jones S Z, Lootens D and Zunino F 2017 *Cement and Concrete Composites* **78** 43–56 URL https://doi.org/10.1016/j.cemconcomp.2017.01.001
[4] Kropyvnytska T, Sanytsky M, Heviuk I and Kripka L 2023 Study of the Properties of Low-Carbon Portland-Composite Cements CEM II/C-M *Proceedings of EcoComfort 2022* ed Blikharskyy Z (Cham: Springer International Publishing) pp 230–237 ISBN 978-3-031-14141-6 URL https://doi.org/10.1007/978-3-031-14141-6_22
[5] Sikora P, Woliński P, Chougan M, Madraszewski S, Węgrzyński W, Papis B K, Federowicz K, Ghaffar S H and Stephan D 2022 *Industrial Crops and Products* **184** 115103 ISSN 0926-6690 URL https://doi.org/10.1016/j.indcrop.2022.115103
[6] Naqi A and Jang J G 2019 *Sustainability* **11**(2) 537 ISSN 2071-1050 URL https://doi.org/10.3390/su11020537
[7] Shen W, Liu Y, Yan B, Wang J, He P, Zhou C, Huo X, Zhang W, Xu G and Ding Q 2017 *Renewable and Sustainable Energy Reviews* **75** 618–628 URL https://doi.org/10.1016/j.rser.2016.11.033
[8] Burciaga-Díaz O 2019 *Cement and Concrete Composites* **103** 104–111 ISSN 0958-9465 URL https://doi.org/10.1016/j.cemconcomp.2019.05.002
[9] Matschei T, Bellmann F and Stark J 2005 *Advances in Cement Research* **17**(4) 167–178 URL https://doi.org/10.1680/adcr.2005.17.4.167
[10] Kropyvnytska T P, Kaminskyy A T, Semeniv R M and Chekaylo M V 2019 *IOP Conference Series: Materials Science and Engineering* **708**(1) 012091 URL https://doi.org/10.1088/1757-899X/708/1/012091
[11] Bai Y, Collier N C, Milestone N B and Yang C H 2011 *Journal of Nuclear Materials* **413**(3) 183–192 ISSN 0022-3115 URL https://doi.org/10.1016/j.jnucmat.2011.04.011
[12] Kryvenko P, Rudenko I and Konstantynovskyi O 2020 *Eastern-European Journal of Enterprise Technologies* **6**(108) 26–40
[13] 2021 Cement–Part 1: Composition, specifications and conformity criteria for common cements Draft Malawi Standard URL http://www.puntofocal.gov.ar/notific_otros_miembros/mwi40_t.pdf
[14] Bernal S A 2016 *RILEM Technical Letters* **1** 39–44 URL https://doi.org/10.21809/rilemtechlett.2016.8

[15] Collier N C, Li X, Bai Y and Milestone N B 2015 *Journal of Nuclear Materials* **464** 128–134 URL https://doi.org/10.1016/j.jnucmat.2015.04.044
[16] Chougan M, Ghaffar S H, Sikora P, Mijowska E, Kukułka W and Stephan D 2022 *Industrial Crops and Products* **178** 114648 URL https://doi.org/10.1016/j.indcrop.2022.114648
[17] Abdel-Gawwad H A, Tawfik T A, Sikora P and Abd Elrahman M 2022 *Construction and Building Materials* **345** 128384 URL https://doi.org/10.1016/j.conbuildmat.2022.128384
[18] Krivenko P, Rudenko I, Konstantynovskyi O and Vaičiukynienė D 2022 *Materials* **15**(9) 3003 URL https://doi.org/10.3390/ma15093003
[19] 2016 National standard of Ukraine DSTU B V.2.7-181:2009 Alkaline cements. Specification URL http://online.budstandart.com/ru/catalog/doc-page?id_doc=65766
[20] Plugin A A, Borziak O S, Pluhin O A, Kostuk T A and Plugin D A 2021 Hydration Products that Provide Water-Repellency for Portland Cement-Based Waterproofing Compositions and Their Identification by Physical and Chemical Methods *Proceedings of EcoComfort 2020* ed Blikharskyy Z (Cham: Springer International Publishing) pp 328–335 ISBN 978-3-030-57340-9 URL https://doi.org/10.1007/978-3-030-57340-9_40
[21] Kropyvnytska T, Semeniv R, Kotiv R and Novytskyi Y 2021 Effects of Nano-liquids on the Durability of Brick Constructions for External Walls *Proceedings of EcoComfort 2020* ed Blikharskyy Z (Cham: Springer International Publishing) pp 237–244 ISBN 978-3-030-57340-9 URL https://doi.org/10.1007/978-3-030-57340-9_29
[22] Plugin A, Borziak O, Miroshnichenko S, Krykun O and Zinchenko V 2022 *AIP Conference Proceedings* **2557**(1) 070004 URL https://doi.org/10.1063/5.0104860
[23] Krivenko P, Rudenko I, Konstantynovskyi O and Boiko O 2021 *E3S Web of Conferences* **280** 07004 URL https://doi.org/10.1051/e3sconf/202128007004
[24] Sikora P, Techman M, Federowicz K, El-Khayatt A M, Saudi H A, Abd Elrahman M, Hoffmann M, Stephan D and Chung S Y 2022 *Case Studies in Construction Materials* **17** e01320 URL https://doi.org/10.1016/j.cscm.2022.e01320
[25] Tsapko Y, Tsapko O and Bondarenko O 2020 *Eastern-European Journal of Enterprise Technologies* **2**(10 (104)) 13–18 URL https://doi.org/10.15587/1729-4061.2020.200467
[26] Tsapko Y, Tsapko A and Bondarenko O P 2020 Research of conditions of removal of fire protection from building construction *Actual Problems of Engineering Mechanics: Materials Science and Technologies* (*Key Engineering Materials* vol 864) (Trans Tech Publications Ltd) pp 141–148 URL https://doi.org/10.4028/www.scientific.net/KEM.864.141
[27] Guo H, Shi C, Guan X, Zhu J, Ding Y, Ling T C, Zhang H and Wang Y 2018 *Cement and Concrete Composites* **89** 251–259 URL https://doi.org/10.1016/j.cemconcomp.2018.03.008
[28] Troian V, Gots V, Keita E, Roussel N, Angst U and Flatt R J 2022 *RILEM Technical Letters* **7** 139–149 URL https://doi.org/rilemtechlett.2022.171
[29] Bu C, Liu L, Lu X, Zhu D, Sun Y, Yu L, OuYang Y, Cao X and Wei Q 2022 *Materials* **15**(3) 1110 URL https://doi.org/10.3390/ma15031110
[30] Kovalchuk O, Grabovchak V and Govdun Y 2018 *MATEC Web of Conferences* **230** 03007 URL https://doi.org/10.1051/matecconf/201823003007
[31] Shi C 2003 *Advances in Cement Research* **15**(2) 77–81 URL https://doi.org/10.1680/adcr.2003.15.2.77
[32] Cyr M and Pouhet R 2015 The frost resistance of alkali-activated cement-based binders *Handbook of Alkali-Activated Cements, Mortars and Concretes* ed Pacheco-Torgal F, Labrincha J A, Leonelli C, Palomo A and Chindaprasirt P (Oxford: Woodhead Publishing) pp 293–318 URL https://doi.org/10.1533/9781782422884.3.293
[33] Moodi F, Norouzi S and Dashti P 2021 *Advances in Concrete Construction* **11**(6) 493—-505 URL https://doi.org/10.12989/acc.2021.11.6.493
[34] Stark J and Wicht B 2001 *Dauerhaftigheit von Beton: der Baustoff als Werkstoff* (Berlin: Birkhäuser)
[35] 2008 National standard of Ukraine DSTU B V.2.7-176:2008 Concrete mixes and concrete. General technical conditions URL http://online.budstandart.com/ua/catalog/doc-page?id_doc=25443
[36] Shi X, Akin M, Pan T, Fay L, Liu Y and Yang Z 2009 *The Open Civil Engineering Journal* **3** 16–27 URL https://doi.org/10.2174/1874149500903010016
[37] Kessler S, Thiel C, Grosse C U and Gehlen C 2016 *Materials and Structures* **50**(2) 121 ISSN 1871-6873 URL https://doi.org/10.1617/s11527-016-0984-4
[38] Wang Q, Yan T and Ding L 2021 *Materials* **14**(8) 1862 URL https://doi.org/10.3390/ma14081862
[39] Millero F J, Feistel R, Wright D G and McDougall T J 2008 *Deep Sea Research Part I: Oceanographic Research Papers* **55**(1) 50–72 URL https://doi.org/10.1016/j.dsr.2007.10.001
[40] Matalkah F and Soroushian P 2018 *Construction and Building Materials* **163** 200–213 URL https://doi.org/10.1016/j.conbuildmat.2017.12.119

[41] Valenza J J and Scherer G W 2007 *Materials and Structures* **40**(3) 259–268 ISSN 1871-6873 URL https://doi.org/10.1617/s11527-006-9104-1
[42] Coppola L, Coffetti D, Crotti E, Gazzaniga G and Pastore T 2020 *Sustainability* **12**(9) 3561 URL https://doi.org/10.3390/su12093561
[43] Provis J L, Palomo A and Shi C 2015 *Cement and Concrete Research* **78** 110–125 URL https://doi.org/10.1016/j.cemconres.2015.04.013
[44] Kharchenco I and Alekseev V 2019 *E3S Web of Conferences* **110** 01037 URL https://doi.org/10.1051/e3sconf/201911001037
[45] Criado M 2015 13 - The corrosion behaviour of reinforced steel embedded in alkali-activated mortar *Handbook of Alkali-Activated Cements, Mortars and Concretes* ed Pacheco-Torgal F, Labrincha J A, Leonelli C, Palomo A and Chindaprasirt P (Oxford: Woodhead Publishing) pp 333–372 URL https://doi.org/10.1533/9781782422884.3.333
[46] Ke X, Bernal S A and Provis J L 2017 Chloride binding capacity of synthetic C-(A)-SH type gels in alkali-activated slag simulated pore solutions *1st International Conference of Construction Materials for Sustainable Future, CoMS2017* (Zadar, Croatia) URL https://www.researchgate.net/publication/316968948
[47] Yuan Q, Shi C, De Schutter G, Audenaert K and Deng D 2009 *Construction and Building Materials* **23**(1) 1–13 URL https://doi.org/10.1016/j.conbuildmat.2008.02.004
[48] Liu Z, Jiao W, Sha A, Gao J, Han Z and Xu W 2017 *Advances in Materials Science and Engineering* **2017** 3927106 URL https://doi.org/10.1155/2017/3927106
[49] Kothari A, Habermehl-Cwirzen K, Hedlund H and Cwirzen A 2020 *Materials* **13**(16) 3467 URL https://doi.org/10.3390/ma13163467
[50] Dong B, Wang F, Abadikhah H, Hao L, Xu X, Khan S A, Wang G and Agathopoulos S 2019 *ACS Applied Materials & Interfaces* **11**(45) 42801–42807 URL https://doi.org/10.1021/acsami.9b14929
[51] Runova R F, Kochevyh M O and Rudenko I I on the slump loss problem of superplasticized concrete mixes *Admixtures - Enhancing Concrete Performance* pp 149–156 URL https://www.icevirtuallibrary.com/doi/abs/10.1680/aecp.34075.0018
[52] Sanytsky M, Kropyvnytska T, Fic S and Ivashchyshyn H 2020 *E3S Web of Conferences* **166** 06007 URL https://doi.org/10.1051/e3sconf/202016606007
[53] Jiao D, Shi C, Yuan Q, An X, Liu Y and Li H 2017 *Cement and Concrete Composites* **83** 146–159 URL https://doi.org/10.1016/j.cemconcomp.2017.07.016
[54] Bispo R A, Vicente G O, da Silva Júnior G P, Benjamim D U and Alcântara M 2021 *Materials Research* **24**(suppl 2) e20210264 URL https://doi.org/10.1590/1980-5373-MR-2021-0264
[55] Revilla-Cuesta V, Skaf M, Santamaría A, Hernández-Bagaces J J and Ortega-López V 2021 *Journal of Cleaner Production* **299** 126890 URL https://doi.org/10.1016/j.jclepro.2021.126890
[56] Krivenko P V, Rudenko I I, Petropavlovskyi O M, Konstantynovskyi O P and Kovalchuk A V 2019 *IOP Conference Series: Materials Science and Engineering* **708**(1) 012090 URL https://doi.org/10.1088/1757-899X/708/1/012090
[57] Krivenko P V, Petropavlovskyi O M, Rudenko I I, Konstantynovskyi O P and Kovalchuk A V 2020 *IOP Conference Series: Materials Science and Engineering* **907**(1) 012055 URL https://doi.org/10.1088/1757-899X/907/1/012055
[58] 2009 National standard of Ukraine DSTU B V.2.7-215:2009 Concretes. Rules of selection of composition URL http://online.budstandart.com/ua/catalog/doc-page?id_doc=25913
[59] 2002 National standard of Ukraine DSTU B V.2.7-114:2002 Fresh concretes. Methods of testing URL http://online.budstandart.com/ua/catalog/doc-page?id_doc=4913
[60] 2008 National standard of Ukraine DSTU B. V.2.7-170:2008 Building materials. Concretes. Methods for determining of average density, humidity, water absorption, porosity and water resistance URL http://online.budstandart.com/ua/catalog/doc-page?id_doc=24882
[61] 1996 National standard of Ukraine DSTU B V.2.7-49-96 Building materials. Concretes. Method for determination of freeze/thaw resistance URL http://online.budstandart.com/ua/catalog/doc-page?id_doc=4950
[62] Troian V V 2016 *Technological bases of increase and prediction of durability massive concrete structures* Ph.D. thesis Kyiv National University of Construction and Architecture

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Sustainable modified pozzolanic supplementary cementitious materials based on natural zeolite, fly ash and silica fume

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Sustainable modified pozzolanic supplementary cementitious materials based on natural zeolite, fly ash and silica fume

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Abstract. The present study examined the effectiveness of pozzolanic supplementary cementitious materials (P-SCMs), such as fly ash (FA), super fine zeolite (SFZ) and silica fume (SF), in reducing the energy intensity and CO_2 emissions of concrete based on ordinary Portland cement. Optimization of the composition of the P-SCMs was carried out by the simplex-lattice Scheffe method according to the criterion of pozzolanic activity. The type and level of P-SCM replacement was analyzed to improve cement paste properties and target CO_2 reduction in concretes. It is shown that the combination of pozzolanic materials of different origin and granulometric composition helps to improve the quality of bended cements and speed up the concrete production process. Blends of pozzolanic P-SCMs results in environmentally friendly concrete with a significant positive impact on the environment. This can be considered the main initiative of sustainability of concrete production.

1. Introduction

An important problem according to the priority areas of the European Green Deal is ensuring carbon neutrality, introducing innovations, modernization and greening of industry. According to the low-carbon development strategy presented by the European Cement Association (CEMBUREAU), it is necessary to reduce carbon dioxide emissions at every stage of the production and technological chain – from the production of clinker, cement and concrete to construction. Already by 2030, it is planned to reduce CO_2 emissions during the production of cement by 30%, and at the stage of concrete production and construction – by 40% [1–5].

Solving the problem of energy efficiency and reducing CO_2 emissions in building production is largely determined by the search for technological and ecological ways to replace a part of Portland cement clinker with supplementary cementitious materials (SCMs). Due to the rational selection of SCMs in the production of low-carbon cements, technical, ecological and economic benefits are achieved [6–8]. Another way is to add SCMs directly to the concrete mixture instead of a part of Portland cement, which helps to reduce the cost of concrete, increase its strength in subsequent periods of hardening, and increase durability. In this case, replacing each kilogram of clinker in concrete with supplementary cementitious materials allows reducing CO_2 emissions by 0.6–1.0 kg [9–12].

One of the main non-clinker constituent, which has been used in cement production for many years, is granulated blast furnace slag (GBFS) [13, 14]. At the same time, rapidly growing consumption of Portland cement as well as low availability of ground granulated blast furnace slag (widely used as SCM) serious steps should be taken to find alternative solution for cement industry. Therefore, there is a growing interest in the use of a by-product of thermal power plants – fly ash. This product is an amorphous vitreous pozzolanic material and, when mixed with cement, significantly affects the strength development of the cementitious composites. Fly ash increases the durability and strength of concrete at a later age, but at the same time reduces the early strength of concrete. It also reduces the amount of water-reducing admixtures required to obtain the same consistency [15–17]. However, the availability of fly ash is also limited in some parts of Europe. Therefore, it is recommended to add other types of pozzolans to the composition of so-called "green" cements together with fly ash. At the same time, with an increased amount of pozzolans, they significantly affect the strength of concrete. Silica fume significantly increases the strength and durability of concrete, but it has a high water demand, so it requires the use of an increased amount of water-reducing admixtures [18, 19].

Significant resources in the European region of natural pozzolans – zeolite tuffs – make it possible to solve the problem of regional application of SCMs [20–22]. High-silica zeolite tuffs (the main mineral is clinoptilolite $(\mathrm{Na, K})_6[\mathrm{Al_6Si_{30}O_{72}}]24\mathrm{H_2O}$) have unique characteristics, such as a high specific surface area and the ability to exchange cations. The introduction of natural zeolites allows binding excess alkalis $(\mathrm{Na^+, K^+})$ into insoluble hydroaluminosilicates as part of inorganic complexes.

The pozzolanic activity of SCMs, which is evaluated by their reactivity, mainly depends on three parameters – the nature of the activity (hydraulic, pozzolanic), the chemical composition of SCMs and their dispersion, while SCMs particles smaller than 10 micrometers are reactive [23–25]. The effectiveness of the increased dispersion of artificial and natural pozzolans is confirmed by the development of ultrafinely dispersed supplementary cementitiouse materials that belong to superpozzolans and provide accelerated binding of calcium hydroxide – a product of the hydrolysis of the alite phase of Portland cement clinker [26, 27]. Such interaction of superpozzolana with products of hydration of Portland cement clinker leads to a decrease in porosity, which helps to increase the strength, corrosion resistance of concrete and determines its durability. However, a high content of finely dispersed SCMs causes an increase in the water consumption of concrete, which leads to a loss of early strength [28–30].

The physical approach opens significant prospects for improving the technical properties of building composites. It consists in not changing the chemical and mineralogical composition of Portland cement clinker, but reducing the water-binder ratio (W/B) of multicomponent cementitious systems and increasing the packing density of binder grains in the cement paste with the help of highly effective superplasticizers, especially of the polycarboxylate type [31, 32].

The creation of modified concretes using multi-component SCMs involves the optimization of their compositions due to the intensification of pozzolanic reactions in the concrete cementitious matrix. The effectiveness of such an idea lies in the maximum disclosure of the synergistic role of highly dispersed pozzolans in the composition of low-carbon cementitious systems, which will ensure a directed effect on the processes of regulating the properties of modified concrete and mortars. The assessment of the indicator of the impact of multi-component SCMs on the environment allows to determine their suitability for the production of low-carbon concrete. In advanced EU countries, $\mathrm{CO_2}$ emissions are reduced to 83.4 kg of $\mathrm{CO_2}$ per 1 ton of concrete. One of the main directions of reducing the $\mathrm{E_{CO_2}}$ indicator is the replacement of a part of Portland cement CEM I type in concrete with multicomponent mineral additives, which is a relevant approach to achieve sustainability in construction industry [33–35].

In recent years, significant attention of researchers and manufacturers has been attracted by alkali-activated binders, which provide significant potential for the development of promising technologies [36–38]. Alkali-activated cementitious materials are characterized by accelerated hardening and are at the epicenter of a new and necessary transition from modern Portland cement to eco-cements of the future. In particular, this technology may soon reach such a stage of development that it will serve as a link for the development of clinker-free alternative binders [39–42].

The purpose of the work is the rational design of the granulometric and material composition of combined pozzolanic SCMs, which, when combined with admixtures of superplasticizing action, create the possibility of obtaining eco-efficient modified blends with specified quality indicators and a reduction in CO_2 intensity per product unit.

2. Raw materials and testing techniques

The Portland cement CEM I 42.5 R JSC "Ivano-Frankivskcement" (Ukraine) was used in experiments. The contents of the main clinker phases, mass.%: C_3S – 61.95; C_2S – 12.31; C_3A – 7.0; C_4AF – 11.75.

Pozzolanic supplementary cementitious materials (P-SCMs) were used for the study:

- natural zeolite with 69.8 mass.% SiO_2 provided from Sokyrnytsky quarry. Super fine zeolite (SFZ) was obtained by grinding natural zeolite to a specific surface area greater than SSA=11000 cm^2/g;
- fly ash (FA) with 57.8 mass.% SiO_2 and 24.2 mass.% Al_2O_3 from Burshtyn TPP, SSA=4100 cm^2/g;
- silica fume (SF) Elkem Microsilica Grade 940-U with 94.7 mass.% SiO_2, SSA=18 000 cm^2/g.

Superplasticizer type polycarboxylate ethers (PCE) was used in this study. Lignosulfonate (LS) was used for comparison.

The chemical composition of fly ash and zeolite was determined using an ARL 9800 XP X-ray spectrometer (Thermo Electron SA, Switzerland). The specific surface of Portland cement and SCMs was determined on Blaine's device. Determination of the strength of blends was carried out in accordance with DSTU B EN 196–1:2015, bleeding in accordance with DSTU B EN 196–3:2015, DSTU B EN 196–6:2015. Pozzolanic activity was determined according to EN 450-1:2009, ASTM C593-06 [43]. According to the methodology based on Italian method, the strength indicators should be $R_f \geq 0.5$ MPa. and $R_c \geq 2.5$ MPa.

The optimization of the composition of pozzolanic supplementary cementitious materials (P-SCMs) was carried out by the simplex-lattice Scheffe method according to the criterion of pozzolanic activity according to EN 450-1:2009. The optimal ratio between P-SCMs components was determined using a simplex-lattice Scheffe "blend-properties" plan to ensure an even spread of experimental points in the factor space. The Gibbs concentration triangle was used in the analysis of the experimental plan. The criterion of pozzolanic activity of P-SCMs according to EN 450-1:2009 was used as the target function. The criteria for the effectiveness of the modifiers (plasticizing and water-reducing effects) were determined according to DSTU B V.2.7-69.

3. Results and discussions

Highly dispersed SCMs such as super fine zeolite and microsilica are characterized by increased water demand – 42.5 and 55.0 %, while having low bleeding (3.0 and 1.0 %, respectively). Fly ash has a lower dispersion compared to other pozzolanic materials. Fly ash is characterized by particles of the correct spherical shape, which provide a plasticizing effect due to the "roller bearing effect". Therefore, its water demand is reduced (27.0 %), but it is characterized by significant bleeding (34 %).

According to EN 450-1:2009, the strength activity index (SAI) after 28 days should be more than 75%, and after 90 days – more than 85%. As can be seen from the figure 1, super fine zeolite and silica fume reach the corresponding indicator of Psai $\geq$ 75% already after 2 days of hardening. The SAI of fly ash meets the requirements of EN 450-1:2009, but is significantly lower compared to super fine zeolite and silica fume.

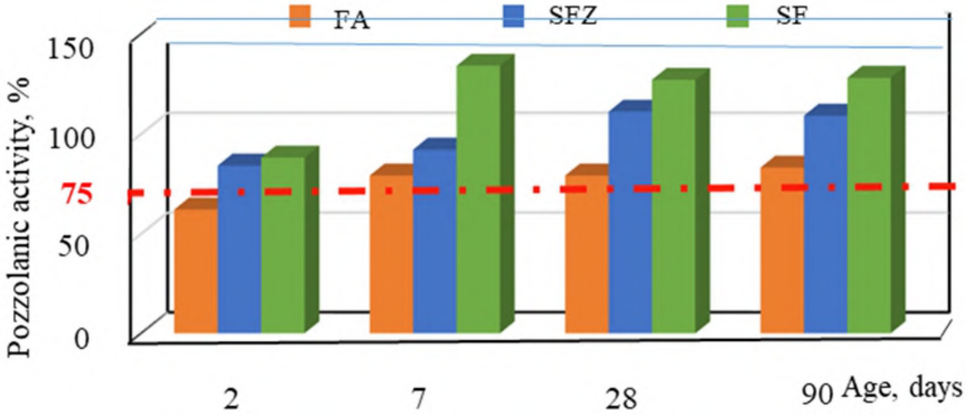

Figure 1. Pozzolanic activity of SCMs according to EN 450-1:2009.

According to ASTM C593-06, the mortar strength for super fine zeolite is 5.2 MPa (requirement $R_c \geq 4.15$ MPa), while for fly ash it is 4.5 MPa. According to the methodology based on Italian method [26], the strength indicators of lime-pozzolan paste in the ratio lime:pozzolan=1:3, for microsilica and super fine zeolite after 28 days of hardening reach 4.6/9.5 MPa and 3.2/7.9 MPa, respectively, and for fly ash – 0.6/1.8 MPa.

The optimal compositions of complex pozzolanic supplementary cementitious materials blends FA – SFZ – SF are determined by the indicator of Strength Activity Index (SAI). The combined effect of components on the pozzolanic activity of P-SCMs after 28 and 90 days of curing was investigated using the Scheffe simplex-lattice plan "blends-property" method. For the three-component mixture "SFZ (X1) : FA (X2) : SF (X3)" each point of the triangular diagram corresponds to one P-SCM ratio. The regression equation, taking into account the significance of the pozzolanic activity coefficients of the P-SCMs blends after 28 and 90 days, is as follows:

$$\mathrm{Psai}_{28} = 84.3456 \cdot X1 + 60.2381 \cdot X2 + 88.7843 \cdot X3 - 20.349 \cdot X1 \cdot X2 - 78.8945 \cdot X1 \cdot X3 - \\ -67.9326 \cdot X2 \cdot X3 + 27.6734 \cdot X1 \cdot X2 \cdot X3.$$

$$\mathrm{Psai}_{90} = 111.4523 \cdot X1 + 76.3598 \cdot X2 + 127.9043 \cdot X3 - 40.641 \cdot X1 \cdot X2 - \\ -88.8047 \cdot X1 \cdot X3 - 35.9429 \cdot X2 \cdot X3 + 8.6034 \cdot X1 \cdot X2 \cdot X3.$$

The analysis of the response function surfaces (figure 2) allows to establish that for the two-component P-SCMs-2, the optimal values of the pozzolanic activity indicators are achieved at the ratio FA : SFZ = 0.46 : 0.54, which after 28 and 90 days are respectively $\mathrm{Psai}_{28} = 94$ % and $\mathrm{Psai}_{90} = 126$ %. At the same time, for the ternary mixture P-SCMs-3, the maximum SAI values are achieved at the ratio FA : SZF : SF = 0.35 : 0.40 : 0.25, with $\mathrm{Psai}_{28} = 99$ % and $\mathrm{Psai}_{90} = 134$ %. When the content of fly ash increases over 60 mass.% in the FA – SFZ – SF pozzolan blends, a decrease in the pozzolanic activity of the combined SCMs is observed. Therefore, the combination of highly active pozzolans (SFZ and SF) with fly ash, which has a plasticizing effect, allows to obtain a three-component pozzolan additive P-SCMs-3, which provides optimal workability and strength of binder.

Studies of the effects of the three-component complex pozzolanic additive P-SCM-3 on the physical and mechanical properties of binders have established that with an increase in the content of P-SCM-3 from 25 to 75 mass.% in the composition of blends, there is an increase in the specific surface from 5900 to 7700 cm^2/g, an increase in water demand by 5.0 %, an extension of the hardening period and a decrease in the bleeding coefficient from 14.4 to 6.8 %. Early strength of blends with a content of 25 mass.% of P-SCM-3 is reduced by only 13 % compared

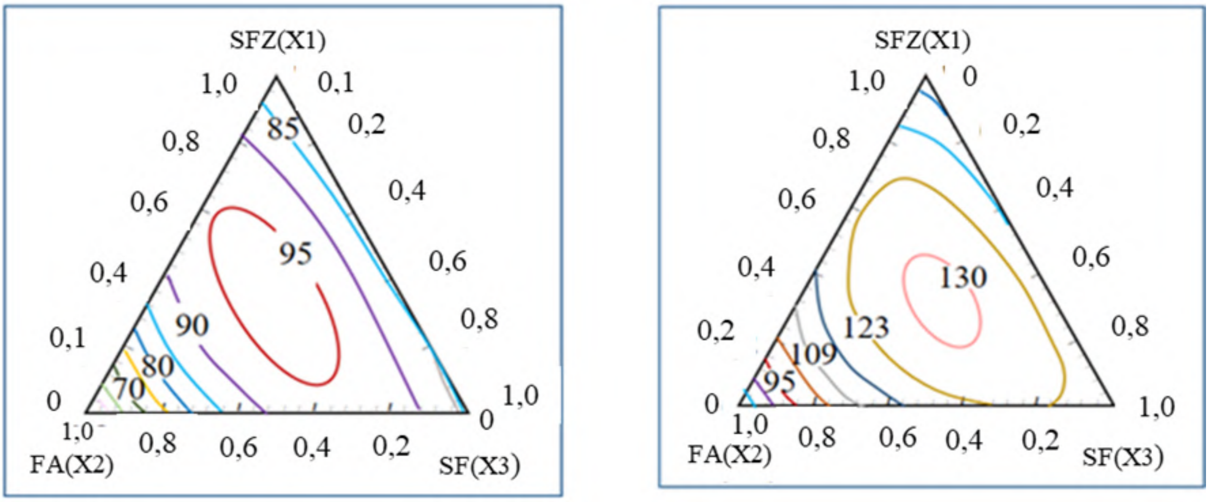

Figure 2. Isolines of effects of the composition of P-SCMs "SFZ – FA – SF" on pozzolanic activity after 28 days (a) and 90 days (b).

to CEM I. With the content of the combined pozzolanic additive P-SCM-3 increases, the early strength decreases proportionally. With a content of 50 mass.% P-SCM-3 in the composition of the blend after 28 days of hardening, the difference in strength is 13 %, that is, due to pozzolanic reactions, a certain increase in strength is achieved. To obtain pozzolanic blends of strength classes 32.5 and 42.5, the effective range of replacing Portland cement CEM I with a combined pozzolanic SCMs is 25...50 mass.%.

Significant reserves of improving the physical and mechanical properties of pozzolanic blends are achieved due to the use of LS and PCE plasticizing admixtures. As can be seen from the table 1, when introducing 1.0 mass.% PCE to blend of 50 mass.% CEM I 42.5R + 50 mass.% P-SCM-3, the flow ability of a standard cone (W/C=0.50) increases from 144 to 290 mm, and when 0.8 mass.% LS is introduced, it increases to 225 mm. For the LS-modified blend, the water-reducing effect is Δ W/C = 14 %, and when modified with 1.0 mass.% PCE – Δ W/C = 22 %. At the same time, the blend modified by PCE is characterized by higher compressive strength (R_{c2} = 20.6 MPa and R_{c28} = 54.4 MPa).

Table 1. Influence of modifiers on the physical and mechanical properties of the blend of 50 mass.% CEM I + 50 mass.% P-SCM-3.

The amount of modifier, %	W/C	Flow, mm	R_{c2}, MPa	R_{c7}, MPa	R_{c28}, MPa
–	0.50	144	11.9	32.5	40.7
		PCE			
1.0	0.50	290	11.9	33.5	38.7
1.0	0.39	145	20.6	38.8	54.4
		LS			
1.0	0.50	225	12.8	24.1	37.3
1.0	0.43	141	18.3	35.6	48.1

By mixing CEM I 42.5R and 50 mass.% P-SCM-3 low-carbon pozzolanic cement type CEM IV (SSA=6850 cm^2/g) was obtained. When tested according to DSTU B EN 196-1:2015, the compressive strength after 2 and 28 days is 15.0 and 44.8 MPa, which corresponds to CEM IV/B 42.5. For this pozzolanic cement, the water demand is 31.5%, the bleeding is 9.1%. Thus, optimization of the granulometric and substance composition of blends allows to obtain low-carbon blended cements of strength class 42.5. Using the method of differential calorimetry, it was established that for this pozzolanic cement the heat of hydration after 24 h decreases by 1.55 times compared to CEM I 42.5 R and is 149 J/g, that is, according to DSTU B EN 197-1:2015, this pozzolanic cement refers to CEM IV/B 42.5– LH.

Carbon dioxide emissions of cement and concrete are significantly reduced with the combined use of FA, SFZ and SF. For blended pozzolanic cements (clinker factor – 0.50) CO_2 emissions are reduced to 456 kg/t, which is 45% less compared to Portland cement CEM I 42.5 R. At the same time, the total energy costs for grinding pozzolana cement (32 kW·h/t) are 40% smaller compared to CEM I. When using complex pozzolanic supplementary cementitious materials, optimization of the properties of binder is ensured: workability, standard and early strength, durability, cost, impact on the environment.

4. Conclusion

Modified multicomponent pozzolanic supplementary cementitious materials (P-SCMs) containing fly ash, super fine zeolite, silica fume, in combination with superplasticizer admixtures, can be effectively used to improve both fresh and hardened properties of concrete. Fly ash is commonly used with silica fume in concrete production to compensate for the slow strength development of fly ash at early ages. The use of super fine zeolite instead of silica fume or its part opens up new opportunities for improving the technological and technical properties of concrete.Technologically optimized blends based on combined pozzolanic SCMs become a rational solution to the problem of improving the energy efficiency of building production. Sustainability assumes that the combination of SCMs with pozzolanic action of different dispersions, based on fly ash, super fine zeolite and silica fume, ensures reduction of CO_2 emissions and cost of concrete production.

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References

[1] Schneider M 2019 *Cement and Concrete Research* **124** 105792 ISSN 0008-8846 URL https://doi.org/10.1016/j.cemconres.2019.105792
[2] Miller S A, John V M, Pacca S A and Horvath A 2018 *Cement and Concrete Research* **114** 115–124 ISSN 0008-8846 Report of UNEP SBCI WORKING GROUP ON LOW-CO2 ECO-EFFICIENT CEMENT-BASED MATERIALS URL https://doi.org/10.1016/j.cemconres.2017.08.026
[3] Shi C, Qu B and Provis J L 2019 *Cement and Concrete Research* **122** 227–250 ISSN 0008-8846 URL https://doi.org/10.1016/j.cemconres.2019.05.009
[4] Kuterasińska J and Król A 2020 *Economic and Environmental Studies* **16**(3(39)) 403–419 URL https://czasopisma.uni.opole.pl/index.php/ees/article/view/3032
[5] Scrivener K L, John V M and Gartner E M 2018 *Cement and Concrete Research* **114** 2–26 ISSN 0008-8846 Report of UNEP SBCI WORKING GROUP ON LOW-CO2 ECO-EFFICIENT CEMENT-BASED MATERIALS URL https://doi.org/10.1016/j.cemconres.2018.03.015
[6] Kapeluszna E, Szudek W, Wolka P and Zieliński A 2021 *Materials* **14**(21) 6423 ISSN 1996-1944 URL https://doi.org/10.3390/ma14216423
[7] Bolte G, Zajac M, Skocek J and Ben Haha M 2019 *Journal of Cleaner Production* **226** 503–514 ISSN 0959-6526 URL https://doi.org/10.1016/j.jclepro.2019.04.050

[8] Samad S and Shah A 2017 *International Journal of Sustainable Built Environment* **6**(2) 663–674 ISSN 2212-6090 URL https://doi.org/10.1016/j.ijsbe.2017.07.003
[9] Lothenbach B, Scrivener K and Hooton R D 2011 *Cement and Concrete Research* **41**(12) 1244–1256 ISSN 0008-8846 Conferences Special: Cement Hydration Kinetics and Modeling, Quebec City, 2009 & CONMOD10, Lausanne, 2010 URL https://doi.org/10.1016/j.cemconres.2010.12.001
[10] Snellings R 2016 *RILEM Technical Letters* **1** 50–55 URL https://doi.org/10.21809/rilemtechlett.2016.12
[11] Juenger M C G and Siddique R 2015 *Cement and Concrete Research* **78** 71–80 ISSN 0008-8846 Keynote papers from 14th International Congress on the Chemistry of Cement (ICCC 2015) URL https://doi.org/10.1016/j.cemconres.2015.03.018
[12] Juenger M C, Snellings R and Bernal S A 2019 *Cement and Concrete Research* **122** 257–273 ISSN 0008-8846 URL https://doi.org/10.1016/j.cemconres.2019.05.008
[13] Giergiczny Z 2019 *Cement and Concrete Research* **124** 105826 ISSN 0008-8846 URL https://doi.org/10.1016/j.cemconres.2019.105826
[14] Sakhno S I, Yanova L O, Pischikova O V and Sergiienko T S 2022 *IOP Conference Series: Earth and Environmental Science* **1049**(1) 012050 URL https://doi.org/10.1088/1755-1315/1049/1/012050
[15] Li Y, Wu B and Wang R 2022 *Construction and Building Materials* **341** 127889 ISSN 0950-0618 URL https://doi.org/10.1016/j.conbuildmat.2022.127889
[16] Wang A, Zhang C and Sun W 2003 *Cement and Concrete Research* **33**(12) 2023–2029 ISSN 0008-8846 URL https://doi.org/10.1016/S0008-8846(03)00217-5
[17] Li G, Zhou C, Ahmad W, Usanova K I, Karelina M, Mohamed A M and Khallaf R 2022 *Materials* **15**(7) 2664 ISSN 1996-1944 URL https://doi.org/10.3390/ma15072664
[18] Kumar P R, Reddy C S and Baig M S 2014 *Cement Wapno Beton* **XIX/LXXXI**(1) 8–16 URL https://www.academia.edu/5043436
[19] Smrčková E, Bačuvčík M and Janotka I 2014 Basic Characteristics of Green Cements of CEM V/A and V/B Kind *Binders and Materials XI* (*Advanced Materials Research* vol 897) (Trans Tech Publications Ltd) pp 196–199 URL https://doi.org/10.4028/www.scientific.net/AMR.897.196
[20] Vejmelková E, Koňáková D, Kulovaná T, Keppert M, Žumár J, Rovnaníková P, Keršner Z, Sedlmajer M and Černý R 2015 *Cement and Concrete Composites* **55** 259–267 ISSN 0958-9465 URL https://doi.org/10.1016/j.cemconcomp.2014.09.013
[21] Yoon C B and Lee H S 2020 *Materials* **13**(15) 3288 ISSN 1996-1944 URL https://doi.org/10.3390/ma13153288
[22] Markiv T, Sobol K, Franus M and Franus W 2016 *Archives of Civil and Mechanical Engineering* **16**(4) 554–562 ISSN 1644-9665 URL https://doi.org/10.1016/j.acme.2016.03.013
[23] Güçlüer K, Ünal O, Günaydın O and Bılen S
[24] Milović T, Šupić S, Malešev M and Radonjanin V 2022 *Sustainability* **14**(5) 2736 ISSN 2071-1050 URL https://doi.org/10.3390/su14052736
[25] Sabet F A, Libre N A and Shekarchi M 2013 *Construction and Building Materials* **44** 175–184 ISSN 0950-0618 URL https://doi.org/10.1016/j.conbuildmat.2013.02.069
[26] Tkaczewska E and Małolepszy J 2009 *Cement wapno beton* **29**(1) 26–33 URL https://www.researchgate.net/publication/281304840
[27] Chen J J, Ng P L, Kwan A K H and Li L G 2019 *Journal of Cleaner Production* **210** 66–76 ISSN 0959-6526 URL https://doi.org/10.1016/j.jclepro.2018.11.007
[28] Zhang J, Wang Q and Wang Z 2016 *Construction and Building Materials* **120** 123–136 ISSN 0950-0618 URL https://doi.org/10.1016/j.conbuildmat.2016.05.100
[29] Sanytsky M, Usherov-Marshak A, Kropyvnytska T and Heviuk I 2020 *Cement Wapno Beton* **25**(5) 416–427 URL https://doi.org/10.32047/CWB.2020.25.5.7
[30] Raghav M, Park T, Yang H M, Lee S Y, Karthick S and Lee H S 2021 *Materials* **14**(23) 7270 ISSN 1996-1944 URL https://doi.org/10.3390/ma14237270
[31] Aïtcin P C and Wilson W 2014 *Cement Wapno Beton* **19**(6) 349–358 URL http://web.archive.org/web/20220407050300if_/http://cementwapnobeton.pl/pdf/2014/2014_6/Aiticin_6_2014.pdf
[32] Sanytsky M, Kropyvnytska T and Kotiv R 2014 Modified Plasters for Restoration and Finishing Works *Proceedings of the Conference on the Rehabilitation and Reconstruction of Buildings CRRB 2013* (*Advanced Materials Research* vol 923) (Trans Tech Publications Ltd) pp 42–47 URL https://doi.org/10.4028/www.scientific.net/AMR.923.42
[33] Mehdipour I and Khayat K H 2017 *Cement and Concrete Composites* **78** 120–131 ISSN 0958-9465 URL https://doi.org/10.1016/j.cemconcomp.2017.01.005
[34] Pushkareva K K, Gonchar O A and Kaverin K O 2019 *IOP Conference Series: Materials Science and Engineering* **708**(1) 012102 URL https://doi.org/10.1088/1757-899X/708/1/012102

[35] Kropyvnytska T, Semeniv R and Ivashchyshyn H 2017 *MATEC Web of Conferences* **116** 01007 URL https://doi.org/10.1051/matecconf/201711601007

[36] Kryvenko P V, Sanytsky M and Kropyvnytska T 2018 Alkali-Sulfate Activated Blended Portland Cements *Binders, Materials and Technologies in Modern Construction IV* (*Solid State Phenomena* vol 276) (Trans Tech Publications Ltd) pp 9–14 URL https://doi.org/10.4028/www.scientific.net/SSP.276.9

[37] Kovalchuk O, Grabovchak V and Govdun Y 2018 *MATEC Web of Conferences* **230** 03007 URL https://doi.org/10.1051/matecconf/201823003007

[38] Krivenko P V, Petropavlovskyi O M, Rudenko I I, Konstantynovskyi O P and Kovalchuk A V 2020 *IOP Conference Series: Materials Science and Engineering* **907**(1) 012055 URL https://doi.org/10.1088/1757-899X/907/1/012055

[39] Krivenko P V, Petropavlovskyi O M, Rudenko I I, Konstantynovskyi O P and Kovalchuk A V 2020 *IOP Conference Series: Materials Science and Engineering* **907**(1) 012055 URL https://doi.org/10.1088/1757-899X/907/1/012055

[40] Krivenko P, Rudenko I, Konstantynovskyi O and Boiko O 2021 *E3S Web of Conference* **280** 07004 URL https://doi.org/10.1051/e3sconf/202128007004

[41] Plugin A A, Borziak O S, Pluhin O A, Kostuk T A and Plugin D A 2021 Hydration Products that Provide Water-Repellency for Portland Cement-Based Waterproofing Compositions and Their Identification by Physical and Chemical Methods *Proceedings of EcoComfort 2020* ed Blikharskyy Z (Cham: Springer International Publishing) pp 328–335 ISBN 978-3-030-57340-9 URL https://doi.org/10.1007/978-3-030-57340-9_40

[42] Krivenko P, Rudenko I, Konstantynovskyi O and Vaičiukynienė D 2022 *Materials* **15**(9) 3003 ISSN 1996-1944 URL https://doi.org/10.3390/ma15093003

[43] Kramar S and Ducman V 2018 *Tehnički vjesnik* **25**(6) 1746–1752 URL https://doi.org/10.17559/TV-20171203193229

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Modelling and experimental studies of the stress-strain state of compressed concrete filled steel tube elements of a continuous section

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Abstract. Modern building structures must meet the requirements of efficiency and resource-saving. The main direction for implementing these requirements is to reduce the consumption of steel (14–16%) and save cement (10–12%). These tasks can be solved through the rational combination of concrete and steel when they work together and the use of high-strength materials. One embodiment of this task is the use of Concrete Filled Steel Tube (CFST) structures. The purpose of this study is to identify the possibility of using the Drucker-Prager model by comparing the results of test studies on short compressed Concrete Filled Steel Tube (CFST) elements with different strength and deformation characteristics of the concrete core to the results from finite element analysis (FEA) modelling of corresponding CFST elements. Additionally, the behaviour of a steel pipe without a concrete core was investigated. The results show that the FEA method used in this work is sufficiently accurate for studying the behaviours of short CFST elements. The modelling technique adopted in the study made it possible to consider the redistribution of stresses in the concrete and pipe dynamically. The stress distribution patterns inside the concrete during both linear and non-linear deformations of CFST elements, as well as the characteristics of the interaction between the concrete and pipe in the contact zone, have been revealed.

1. The problem formulation and its relationship with scientific and practical tasks

The construction of modern buildings and structures requires the use of compressed elements with a high bearing capacity. One of the solutions to this problem is the use of Concrete Filled Steel Tube (CFST) elements. However, the wide distribution of this type of structural element is their significant metal consumption. In compressed CFST elements, the load is taken by both the pipe shell and the concrete core [1, 2]. Increasing the bearing capacity of the core helps to reduce steel consumption while maintaining the bearing capacity of the CFST element [3]. In the limiting state, CFST does not collapse in the conventional sense. Because the destroyed concrete reinforced by the shell is included in the joint work. That is, the combination of one structural element of several components from different structural materials leads to the formation of a special state of interaction between them. Therefore, the use of a rationally selected core will lead to a significant reduction in the need for metal and cost savings during the construction of the structure. Thus, the study of the behaviour of solid section elements compressed by CFST will allow choosing of the most effective design solutions for such structures. Modern FEA methods for simulating the behaviour of structures allow you to get significant savings in time and resources when checking the correctness of the design decisions made. However, to ensure the similarity of mathematical and physical models, it is necessary to use modern models of the behaviour of materials, in particular, concrete.

2. Research and publications analysis

At present, buildings and structures designed and built using CFST are represented almost all over the world. At the moment, the robot TB under static loading has been widely studied. In work [4] stress-strain state CFST was estimated using the complex variable apparatus. The resulting solution is exactly within the boundaries of the formulated prerequisites. The key of which is the continuous joint work of individual components (pipe and concrete core) at all stages of loading until the limit state is reached. An analysis of the comparison results revealed that satisfactory agreement between theoretical and experimental studies was only for samples with a core of ordinary heavy concrete of low and medium ranges of strength classes. Thus, this approach limits the possibility of extending the obtained solution to CFST elements with other component materials, for example, high-strength concretes. In addition, the results obtained cannot be extended to other design solutions other than a solid two-component CFST element. For example, elements with voids in a concrete core, reinforced cores, etc. In the work [5] the method of estimating the stress-strain state based on the mechanical model of a composite body is considered. This approach makes it possible to take into account the loss of contact interaction between individual CFST components. This adequately describes the operation of a CFST element with a wide range of physical and mechanical characteristics of the components. In addition, the general methodological approach allows us to consider any design solutions for the CFST element, for example, to take into account additional bar reinforcement, etc. But a significant drawback is the laborious process of forming a system of resolving equations for the skin of such design solutions. At the same time, the issue of ambiguity in the conduct of calculations for such structures hinders the wider introduction of this kind of combination of steel and concrete, including taking into account the strengthening of their cores. The aim of the research was to formulate the prerequisites for performing an analytical calculation of compressed CFST elements with a high-strength core, as well as to evaluate the effectiveness of structural CFST elements with hardened cores compared to steel elements.

Due to many advantages that draw attention to the presented designs [6, 7], previous studies were aimed at clarifying the mechanism of development of the stress-strain state of CFST elements with a hardened core for a more reliable and specific assessment of their characteristics [8–15].

Previous CFST studies using FEA [16–22] have shown that it is possible to accurately model the behaviour of this type of structural element. However, most of the considered models worked only at the stage of linear deformations of the concrete core. The study of the nonlinear behaviour of concrete was hampered by the lack of software implementation of nonlinear models of concrete behaviour, such as the Drucker-Prager model.

3. Formulation of the problem

Combining the geometric parameters and mechanical properties of the materials of the CFST components provides a variety of design options. Each of them has its own advantages and disadvantages. This creates uncertainty in the final decision. The choice can be made only by having an idea about the work under a load of a particular design solution. The developed methods for designing CFST structures, which are based on exact mathematical solutions, are cumbersome and limited in application. For adequate modelling of the stress-strain state of complex structural elements, it is not enough to imagine a model in which individual elements have excellent mechanical characteristics. The transition between different stress-strain state CFST structures throughout their life cycle is caused by a change in the magnitude and direction of external force factors. Therefore, the search for an adequate mechanism for assessing the stress-strain state of CFST structures is relevant.

The purpose of this study is to identify the possibility of using the Drucker-Prager model by comparing the results of test studies of short CFST elements with different strength and deformation characteristics of the concrete core with the results of FEA modelling of the corresponding CFST elements.

4. Statement of material and results

4.1. Methodology for conducting test studies

The purpose of this study is to identify the possibility of using the Drucker-Prager model by comparing the results of test studies of short CFST elements with different strength and deformation characteristics of the concrete core with the results of FEA modelling of the corresponding CFST elements.

Samples were tested after 28 days of natural hardening. Samples were tested in a GSM-250 press. The samples were loaded through the hinges along the longitudinal physical axis, the position of which was established by the trial loading method. The loading steps were 0.1 of the expected breaking force at the beginning of the test and 0.05 before reaching the ultimate limit state.

Longitudinal deformations during the testing of samples were measured using dial gauges with a division value of 0.01 mm. Simultaneously, the deformations in the compressed elements were measured using electric strain gauges. The AID-2M device was used to take the indicators. Each electric strain gauge was connected to an AID-1 measuring device, through which deformations were recorded.

The mechanical characteristics of the metal were determined by testing empty pipes for compression. Tensile strength was determined on standard samples-strips cut from the walls of pipes. The test results are given in table 1. The characteristics of concrete were determined

Table 1. Physical and mechanical characteristics of steel pipes.

Sample Series	Pipe diameter and wall thickness D_{xt}, mm	Compressive strength, MPa	
		R_y	R_u
P	163.0×5.5	317	475

by testing concrete prisms. The longitudinal and transverse deformations were measured with the help of electric strain gauges. Longitudinal strains were also measured with dial gauges. According to the results of the test, graphs of the dependence of deformations on stress $\sigma - \epsilon$ were plotted, the prismatic strength was determined, and Young's modulus and Poisson's ratio of concrete were calculated. The cubic strength of concrete was determined by testing cubes with an edge of 150 mm. The deformation - strength characteristics of concrete are given in table 2.

Table 2. Deformation - strength properties of concrete.

Sample Series	$f_{ck,cube}$, MPa	$f_{ck,prism}$, MPa	$E_b \times 10^{-4}$, MPa	ν
CFST 1	26.8	18.8	1.98	1.98
CFST 2	82.3	64.2	2.20	0.14
CFST 3	98.7	80.0	2.40	0.13

4.2. Modelling method adopted in the work
The modelling of the operation of CFST elements was carried out considering the nonlinear function of the components. The calculation was carried out considering large deformations. By the task, the CFST elements have a symmetrical tubular section and a central load case, to reduce the size of the model and reduce computational costs, the analysis was carried out considering the modelling of cyclic symmetry. In this case, the behaviour of one symmetrical sector (1/4 of the tubular component) was calculated, and the results obtained were used to build the response behaviour of the full component (as a post-processing step).

The simulation was carried out using the non-commercial software ANSYS Student by the finite element method in the Workbench environment. The non-linear calculation of CFST elements was carried out considering the concrete work model – Drucker-Prager and taking into account the multilinear isotropic hardening of steel. The joint work of the steel pipe and the concrete core in the model was provided by frictional contact. Following studies [18], the friction coefficient was taken equal to 0.5 in the simulation. [23].

Three models of CFST elements were analysed, which had the same external diameter of 119 mm but differed in the strength of the concrete core. In addition, the behaviour of a steel pipe without a concrete core was investigated.

4.3. Features of concrete modelling
The Drucker-Prager model was used to simulate the behaviour of concrete, which describes the nonlinear behaviour of concrete and is based on the theory of plastic flows. The calculation of the parameters of the Drucker-Prager model was carried out according to the methods proposed in the works [24–29]. The validity of the accepted parameters was tested in the work [30].

The parameters given in table 3 were used in the calculations of the behaviour of concrete.

4.4. Features of steel modelling
Considering large plastic deformations, the steel pipe material model was developed considering multilinear isotropic hardening. Non-linear steel curves are found in Figure 1, and steel structural information data are presented in table 4.

4.5. CFST FEA model
When preparing the mathematical model, the parametric design was applied, which allows changing the model when its geometry changes. CAD models were created in SpaceClaim. Models were transferred to ANSYS Workbench via a direct interface.

The contact between the concrete core and the steel pipe was assumed in the calculations as Frictional, with a friction coefficient of 0.5. The connection between the base plates and the pipe was set as Bonded and between the base plates and the pipe was Frictionless.

All elements were modelled using SOLID186 hex elements. The SOLID186 element is defined by 20 nodes having three degrees of freedom per node. The element maintains ductility, hyperelasticity, creep, large deflections, and large stresses. The size of the concrete element

Table 3. Concrete parameters of CFST FEA models.

Parameters	CFST-1	CFST-2	CFST-3
Young's Modulus, MPa	19800	22000	24000
Poisson's Ratio	0.16	0.14	0.13
Bulk Modulus, MPa	9705.9	10185	10811
Shear Modulus, MPa	8534.5	9649.1	10619
Drucker-Prager Base			
Uniaxial Compressive Strength, MPa	18.8	64.2	80
Uniaxial Tensile Strength, MPa	2.12	4.25	5.01
Biaxial Compressive Strength, MPa	26.86	83.75	115.73
Softening			
Active Table	Linear	Linear	Linear
Plastic Strain at Uniaxial Compressive Strength	0.00194	0.00292	0.0028
Ultimate Effective Plastic Strain in Compression	0.009739	0.03007	0.0352
Relative Stress at the Start of Nonlinear Hardening	0.4	0.4	0.4
Residual Compressive Relative Stress	0.93	0.93	0.93
Plastic Strain Limit in Tension	0.000889	0.000889	0.000889
Residual Tensile Relative Stress	0.5	0.5	0.5
Dilatancy			
Tensile and Tension-Compression Dilatancy	0.25	0.25	0.25
Compression Dilatancy	1	1	1
Density, kg/mm^3	2.30E-06	2.30E-06	2.30E-06

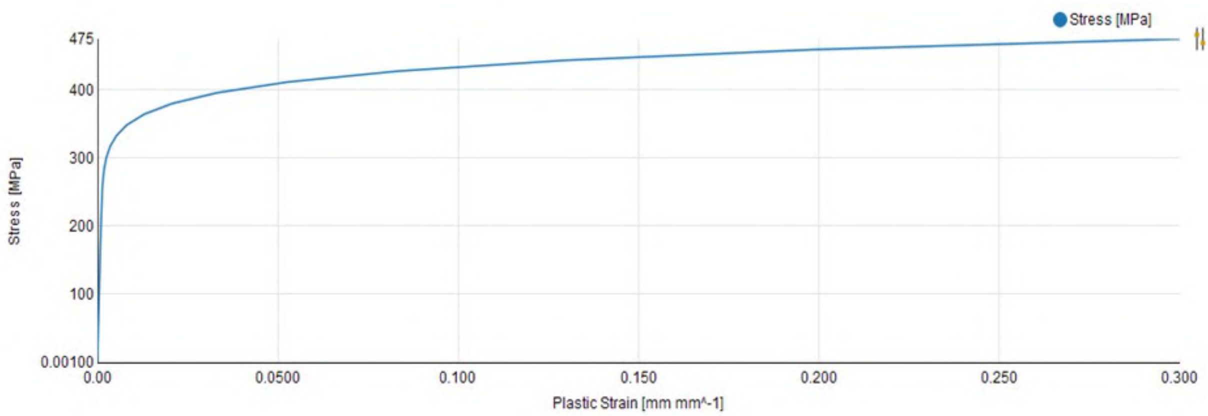

Figure 1. The curve of isotropic hardening of pipe material.

was taken equal to 15.2 mm, for the pipe - 5.5 mm. The size of the elements of the base plates was assumed to be 32 mm (figure 2).

The boundary conditions of the lower support plate were modelled as Fixed Support (figure 3). To improve the convergence of the matrix, the elements were loaded not through the application of a load, but through deformations. Therefore, the boundary conditions of the upper base plate were modelled as Displacement along the Y-axis. The displacement was carried out step by step in equal shares. In total, during 10 steps, the plate was displaced by 30 mm. The CFST behaviour was studied at each loading step.

Table 4. Steel characteristics in CFST FEA models.

Parameters	Value
Young's Modulus, MPa	2.10E+05
Poisson's Ratio	0.3
Bulk Modulus, MPa	1.75E+05
Shear Modulus, MPa	80769
Density, kg/mm^3	7.85E-06

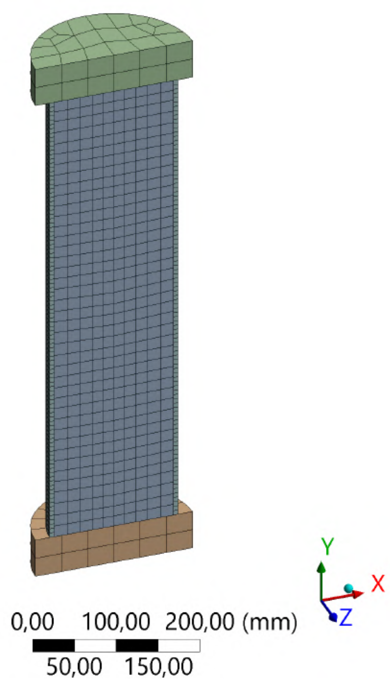

Figure 2. CFST element FEA model.

4.6. Results comparison of simulation and natural experiments

The dependences of deformations of CFST elements on the load were obtained because of test and FEA studies. The results are shown in figure 4 and figure 5. A comparison of the two groups of results shows that the simulation method used in the work is sufficiently accurate to study the behaviour of short CFST. Particularly good correlation is obtained in the region of linear deformations CFST. This allows us to conclude that the proposed method can be used to predict the strength characteristics of CFST elements.

The proposed method also made it possible to "look inside" CFST elements and obtain data that is difficult to obtain as a result of laboratory tests. The stress distribution patterns inside the CFST components at different loading levels are obtained. For example, figure 6 shows the distribution of equivalent stresses for sample CFST-2 at a load of 871 kN. It has been observed that the stresses within the volume of the concrete core are distributed unevenly. The modelling technique utilized in this study enables consideration of the redistribution of stresses within both the concrete core and pipe dynamically. Within the region of linear deformations, the stress distribution of the stress element at the centre of the concrete core and pipe did not

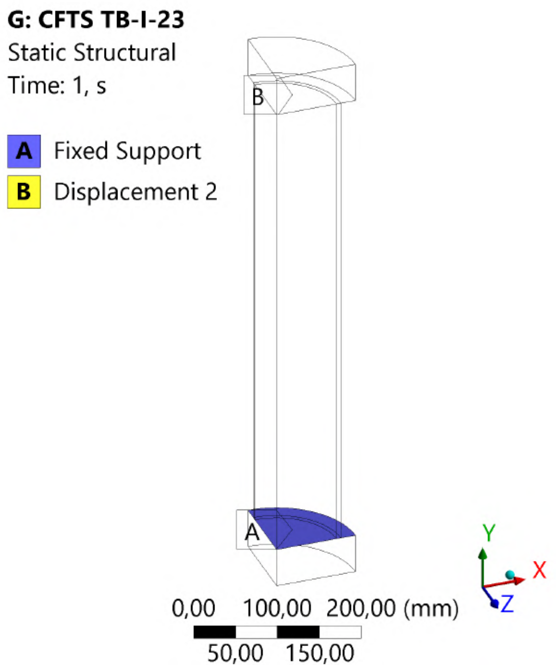

Figure 3. Boundary conditions of CFST element FEA model.

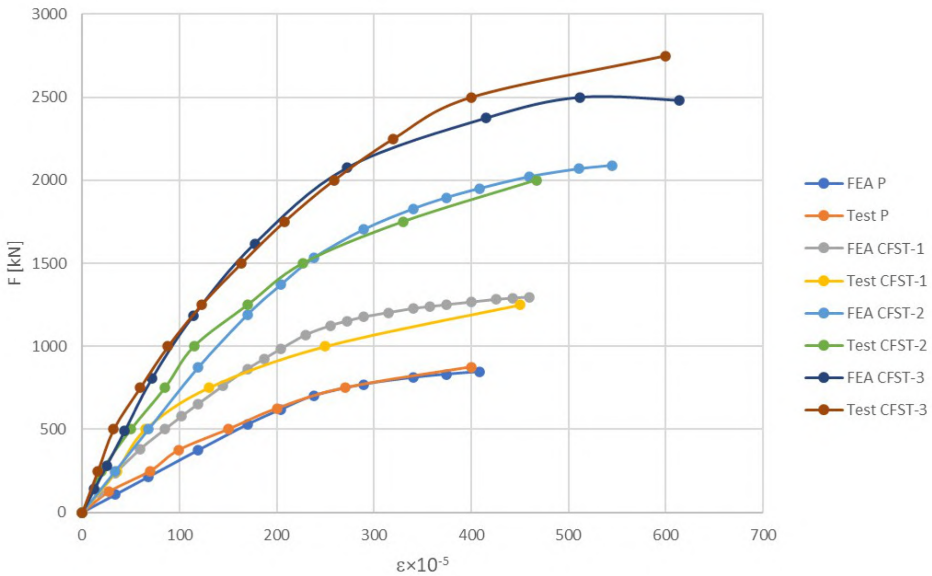

Figure 4. The longitudinal strain of a metal pipe and CFST elements.

differ. However, upon transitioning to the zone of non-linear deformations, the stresses in the longitudinal axis of the concrete core were found to be higher than those in the contact zone with the pipe.

Figure 7 shows the information on the Sliding Distance between the concrete core and the pipe for sample CFST-3 at a load of 2339 kN. Displacement of concrete relative to the pipe was observed in the edge zones adjacent to where the elements were fixed. The maximum

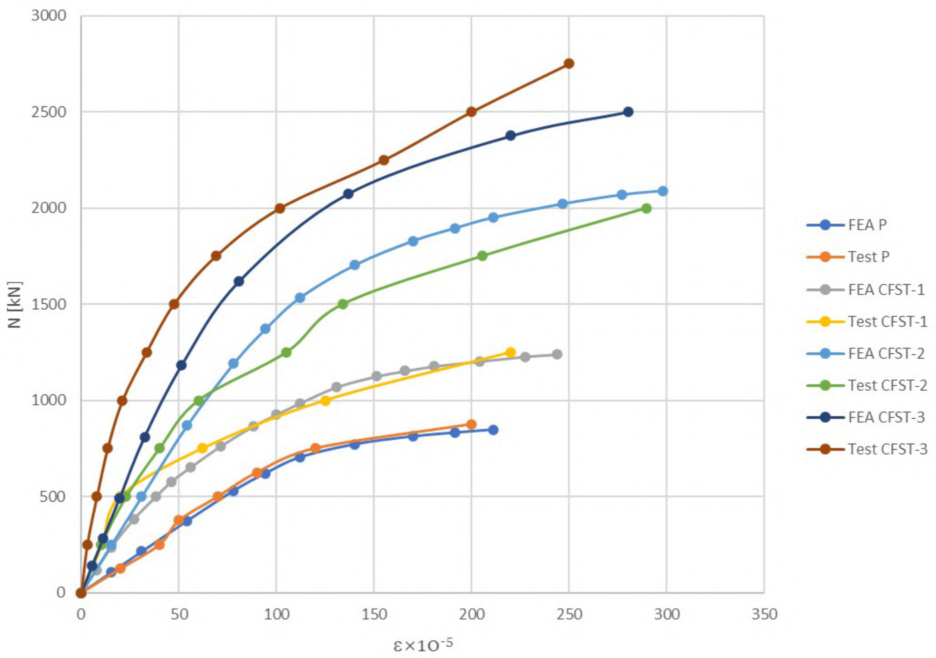

Figure 5. The transverse strain of a metal pipe and CFST elements.

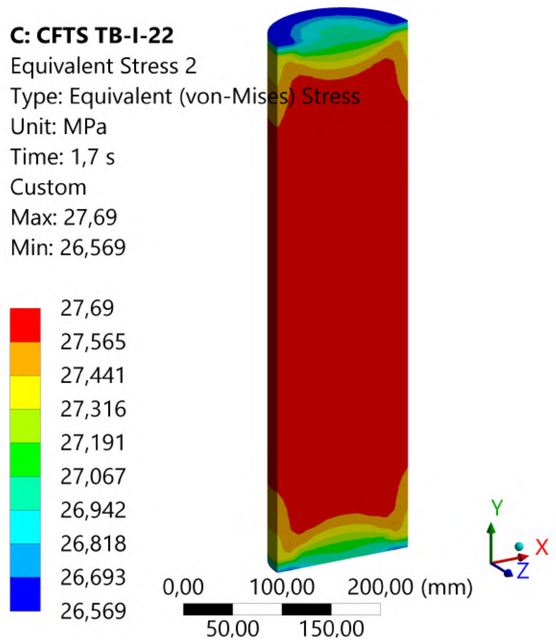

Figure 6. Distribution map of equivalent (von Mises) stress in sample CFST-2 at 871 kN.

displacements were found at a distance of approximately 1/8 of the element length from the fixing planes, where the maximum frictional stresses were also observed. In the central part of the CFST element, no displacement of concrete relative to the pipe was observed. As the transition from linear to non-linear deformations occurred, a gap was observed between the concrete and the pipe, with a value of approximately 0.05-0.06 mm for the middle part of the

CFST element. Before and after this transition, no gap was observed between the concrete and the pipe.

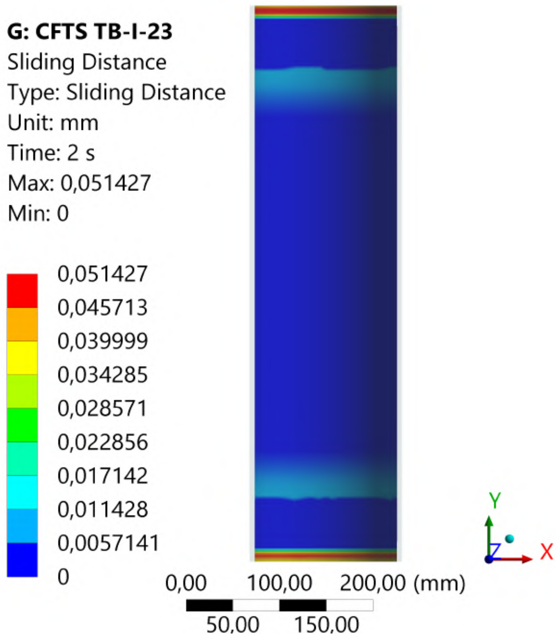

Figure 7. Sliding Distance between concrete core and pipe for sample CFST-3 at 2339 kN.

5. Conclusion

In this work, a comparison of the results of test studies of short CFST elements with different strength and deformation characteristics of the concrete core with the results of FEA modelling of corresponding CFST elements was carried out. This study's conclusions can be summarized as follows:

- The Drucker-Prager model, for which the parameters were calculated based on existing methods and verified for their adequacy, was used to model concrete.
- A model with multilinear isotropic hardening, for which a nonlinear stress-strain curve was set, was used to model steel.
- Parametric design, contact conditions, boundary conditions and step loading were used in the modelling.
- The study showed sufficient accuracy and adequacy of the proposed method for studying the behaviour of short CFST elements.
- The high degree of convergence between modelling and test results provides the possibility of using the Drucker-Prager model to model the behaviour of compressed CFST elements with different characteristics of strength and deformation of the concrete core.
- The application of the FEA method allows for a deeper study of the mechanism of interaction between the concrete core and the steel pipe.
- The proposed method made it possible to reveal the features of stress and displacement distribution in the components of CFST elements, which were detected by modelling and which are difficult to obtain by laboratory studies. In particular, unevenness of stresses in the concrete core, displacement of concrete relative to the pipe in the edge zones and appearance of a gap between concrete and pipe in the transitional regime were observed.

– The features of stress distribution inside the concrete core both in linear and nonlinear deformations of CFST elements, as well as the features of interaction between concrete and pipe in the contact zone, were revealed.

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References

[1] Huang C S, Yeh Y K, Liu G Y, Hu H T, Tsai K C, Weng Y T, Wang S H and Wu M H 2002 *Journal of Structural Engineering* **128**(9) ISSN 0733-9445
[2] Kuranovas A and Kvedaras A K 2007 *Journal of Civil Engineering and Management* **13**(4) ISSN 18223605
[3] wu Yu Z, xing Ding F and Cai C S 2007 *Journal of Constructional Steel Research* **63**(2) ISSN 0143974X
[4] Storozhenko L I and Vasyuta V B 2002 *Municipal economy of cities* **38** 50–52 ISSN 2522-1809
[5] Storozhenko L I and Yermolenko D A 2010 *Bulletin of Lviv Polytechnic National University* **662** 350–354
[6] Mohilevtseva I N and Razumova O V 2012 *Visnyk pgsa* **1-3** 45–53
[7] Yefimenko V I and Sukhan A P 2008 *Build. Constr.* **70** 96–102
[8] Li G, Hou C, Shen L and Yao G H 2022 *Journal of Constructional Steel Research* **188** ISSN 0143974X
[9] Dong Y, Pan Y, Wang D and Cheng T 2022 *Construction and Building Materials* **322** 125877 ISSN 0950-0618 URL https://www.sciencedirect.com/science/article/pii/S0950061821036102
[10] Palyvoda O A 2016 *Journal of Engineering Academy of Ukraine* **1** 263–266
[11] Chen S, Zhang H, Hou C, Han L H and Mu T M 2021 *Structural Safety* **89** ISSN 01674730
[12] Reddy G S R, Bolla M, Patton M L and Adak D 2021 *Structures* **29** ISSN 23520124
[13] Zhang F, Xia J, Li G, Guo Z, Chang H and Wang K 2020 *Materials* **13**(3) ISSN 19961944
[14] Javed M F, Farooq F, Memon S A, Akbar A, Khan M A, Aslam F, Alyousef R, Alabduljabbar H and Rehman S K U 2020 *Crystals* **10**(9) ISSN 20734352
[15] Hasan H G, Ekmekyapar T and Shehab B A 2019 *Marine Structures* **65** ISSN 09518339
[16] Yang Y F and Han L H 2011 *Thin-Walled Structures* **49**(2) ISSN 02638231
[17] Han L H, Hou C C, Zhao X L and Rasmussen K J 2014 *Journal of Constructional Steel Research* **92** ISSN 0143974X
[18] Hu C M, Han L H and Hou C C 2018 *Journal of Constructional Steel Research* **146** ISSN 0143974X
[19] Yang X, Zhu Y, Yang H and Zhang S 2019 *Jianzhu Jiegou Xuebao/Journal of Building Structures* **40** ISSN 10006869
[20] Hou C, Han L H, Mu T M and He S H 2017 *Journal of Constructional Steel Research* **134** ISSN 0143974X
[21] Liu J Q, Han L H and Zhao X L 2017 *Thin-Walled Structures* **120** ISSN 02638231
[22] Han L H, Yao G H and Tao Z 2007 *Thin-Walled Structures* **45**(1) ISSN 02638231
[23] Espinós C R G and Manuel L 2013 *Colección Académica. Editorial UPV* **1** 55
[24] Mirmiran A, Z K and Yuan W 2000 *Finite elements in analysis and design* **35**(1) ISSN 0168874X
[25] Standard E 2004 *Eurocode 2*
[26] Hu H T, Huang C S, Wu M H and Wu Y M 2003 *Journal of Structural Engineering* **129** 1322–1329
[27] Xu T, Xiang T, Zhao R and Zhan Y 2010 *Structural Engineering and Mechanics* **35**(3) ISSN 12254568
[28] Hu H T, Huang C S and Chen Z L 2005 *Journal of Constructional Steel Research* **61**(12) ISSN 0143974X
[29] Kupfer H, Hilsdorf H K and Rusch H 1969 *Journal proceedings* **66**(8) 656–666
[30] Sakhno S, Lyulchenko Y, Yanova L and Pishchikova O 2020 *Mining Journal of Kryvyi Rih National University* **108** 27–34 ISSN 2306-5435

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Influence of deformation degree on grains size and borders between them in metal alloys during cold rolling of sheets

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Influence of deformation degree on grains size and borders between them in metal alloys during cold rolling of sheets

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Abstract. The internal structure of metal products was investigated and it was identified that it affects quality and workability of equipment parts. Changes that occur in metal products structure during cold treatment by pressure, which lead to changes in physical and mechanical properties of products, have been analyzed. It was established that grains and borders between them, which determine internal structure of metal products, change their shape and size during cold rolling, depending on percentage reduction value. It is offered to consider grain borders as amorphous layer. Methodology has been developed to study influence of deformation degree during cold rolling to grain size of metal internal structure and intergranular layer volume. Intergranular surface area, its volume and part of surface volume from metal volume were determined. Parameters of internal structure of low-carbon steel were calculated depending on reduction value during cold rolling. According to study results, interconnection between grains size and deformation degree was established; and percentage reduction influence to grain size and borders between them was determined, obtaining a minimum standard grain size with percentage reduction of over 80 %; yield strength and its growth for metal alloy during cold rolling are established, which allows controlling the strength of steel by adjusting the grain size and their junction surface. It is shown that with an increase in deformation degree, yield strength of metal product material increases in hyperbolic dependence, and fraction of amorphous layer and strength properties of low-carbon steel change almost equally in exponential functions. It is revealed that during cold rolling, it is possible to control internal properties of obtained product by adjusting reduction value.

1. Introduction

During the process of mechanisms and machines structures manufacture, requirements for their strength, quality and reliability are constantly increasing. Detail properties are determined by internal structure of metal, which was used for manufacturing. In order to improve metal products quality, it is necessary to find opportunity to control strength of metal and alloys during their manufacture, due to improving internal structure of metal products.

Metals and alloys have certain properties that are divided into physical (specific weight, melting point, heat capacity, electrical conductivity, linear expansion coefficient, magnetic properties); mechanical (strength, hardness, resistance to impact, resistance to fatigue), which determine metals workability; technological (forging property, flowability, weldability, machining by cutting), which determine ability of metals and alloys to undergo different methods of hot and cold processing; chemical (corrosion resistance, high-temperature resistance, high-temperature strength), which determine stability of metals in aggressive environments at normal and high temperatures. All these properties depend on nature of metal and its internal structure, which consists of grains of various sizes. The finer grains in internal structure of metal are, the higher its strength and plastic properties. Therefore, investigation of metal structure change under influence of external factors is a relevant problem, and solution of this problem will enable to manage steel strength during rolling by means of identification of rational treatment modes and will improve metal products quality.

2. Analysis of literature data and problem definition

Within the framework of the program of stable development of metallurgy, the team of scientists of the Department of Metallurgy of Ferrous Metals and Foundry Production of the Kryvyi Rih National University is solving the following important tasks: improving the technology of foundry and rolling production and improving the quality of manufactured products [1, 2].

For correct choice of material for mechanisms structures manufacture with further adding mechanical and other properties that affect reliability and workability of machines, it's necessary to know internal structure of material at micro level. Metals and alloys consist of large number of small crystals of irregular shape – grains and borders between them [3,4]. Borders between grains form inner surface of metal. This surface area is area of intergranular borders in units of volume or mass of metal [5–7]. As it can be seen from sources, inner surface parameters significantly affect mechanical properties of metal products. Mentioned surface is characterized by its value, which depends on grains number and size (diameter), dislocations density, metal porosity and density, disorientation (angles magnitude between grains surfaces) and other parameters, i.e. thickness and volume of surface and fraction volume from total metal volume.

Structural features of crystalline grids of metals and alloys are formed when they crystallize. The faster cooling (crystallization) of melt is carried out, the more and smaller size of equiaxial grains is formed. Distance between the nearest atoms (crystal grid parameter) is less in completely solidified steel comparing to liquid state [6]. During solid steel cooling, grains jointing in it continues due to atoms diffusion, which is accompanied by decrease in intergranular borders. In this case, smaller grains having a larger surface curvature are gradually absorbed by larger grains with less surface curvature. Diffusion process is known of being quite slow. There may also be other behavior of grains and intergranular borders in steel during products deformation: they change shape, collapse, forming new additional surfaces due to grains crushing and formation of new dislocations – vacancies, pores and cracks [4, 6, 7].

During treating metals by pressure, plastic deformation of original material occurs, and it causes changes in its shape and size (figure 1) [2].

During cold rolling hammering harden, grinding and elongation of ferrite grains along the rolling direction occurs. Summarized reduction during cold treatment determines final texture of deformed material. In case of high degree of cold deformation, fine grain is formed. Ability of metals and alloys to plastic deformation is determined by material yield strength, which also depends on its internal structure. Metal alloys yield strength can change with treatment by pressure, which is especially noticeable during metal rolling of cold state. During metals treatment by pressure or during heat treatment, material strength and plasticity change due to change in internal structure – grains are crushed or enlarged, and number of dislocations or vacancies decreases in grains, pores appear and disappear, that means that junction surface between grains changes in metals volume [3, 4]. During cold rolling metal density usually decreases. This is due to the fact that during deformation intergranular cavities and cracks are formed.

Investigation of yield strength and its change under influence of external factors was carried out in works of [8–13].

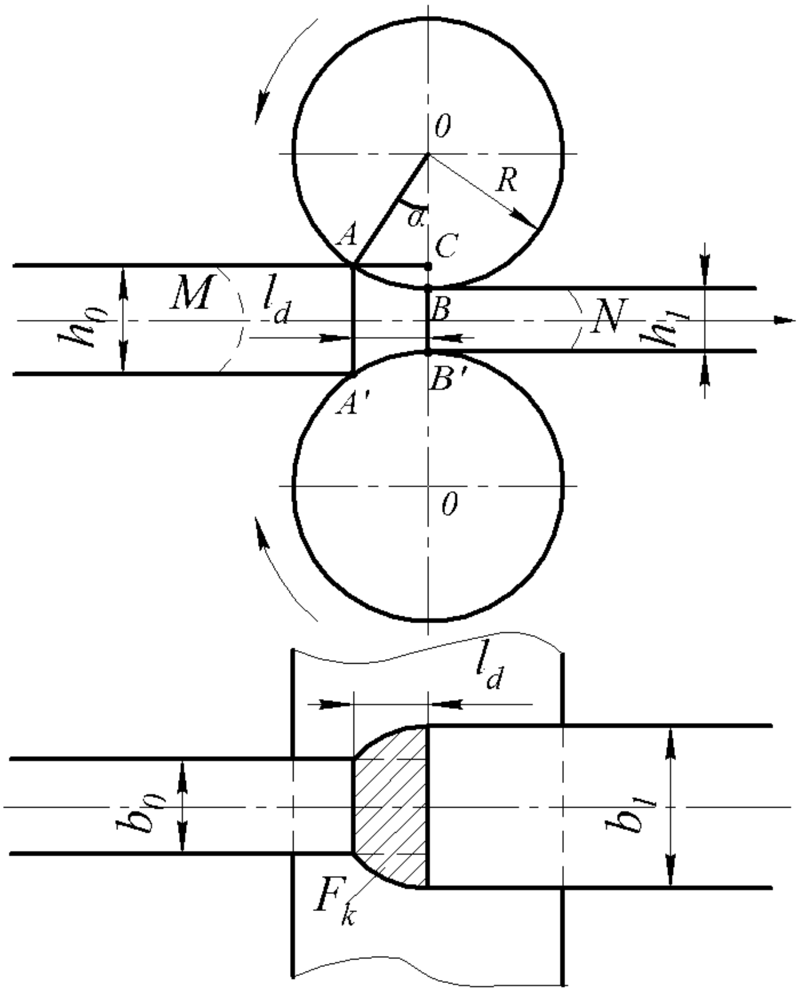

Figure 1. Deformation scheme: $ABB'A'$ is strain zone; h_0 is sheet thickness before rolling; h_1 is sheet thickness after rolling; b_0 is strip width before rolling; b_1 is strip width after rolling; α is capture angle during rolling; h_0, h_1 – initial and final thickness of strip accordingly R is roll radius; F_k is contact area of the sheet with the rolls; l_d is length of the strain zone; M is metal flow before entering the strain zone; N is metal flow when leaving the strain zone.

According to authors, research in this area shall be continued and influence of reduction value during cold rolling on grain size and borders between them shall be considered, which will allow to control strength and plasticity of products by adjusting value of reduction during cold rolling of steel.

3. Purpose and tasks of research

Purpose of work: to analyze influence of deformation degree during cold rolling on grain size and volume of metal internal structure joint surface

In order to reach this goal, following tasks were set: to determine dependencies between metal alloy grains size and borders between them from reduction value during cold rolling; to establish regularities of the impact of the amount of crimp on the grain sizes of the metal alloy, the boundaries between them and the strengthening of the metal.

4. Methodology of research

Low-carbon steel was used in research. The microstructure of cast low-carbon steel (figure 2) was studied and compared with the structure after cold rolling (figure 3), which shows the changes in the shape and size of the grains during pressing.

Using data from list of references [14, 15], geometric characteristics of metal were identified, i.e. intergranular surface area and its volume, and surface volume fraction from metal volume.

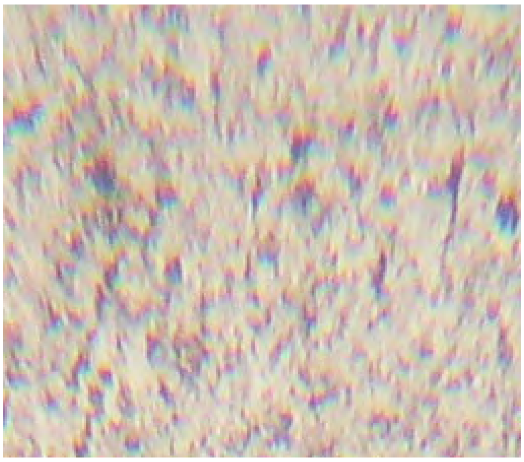

Figure 2. Microstructure of cast low-carbon steel.

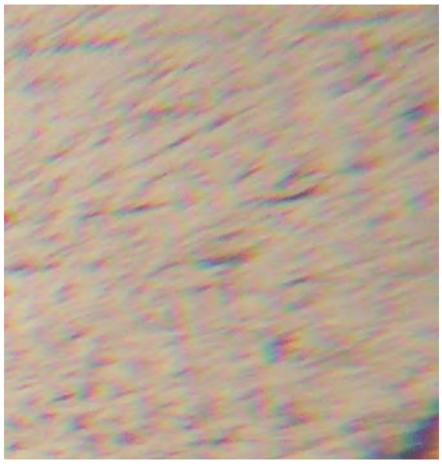

Figure 3. Microstructure of low-carbon steel after rolling.

Intergranular surface volume V_{MZ} was calculated according to formula:

$$V_{MZ} = 3t \cdot d_z^2 n, \tag{1}$$

where d_z – grain size in form of cube, m; n – number of grains, contained in 1 m^3; t – intergranular surface thickness, $t = 0{,}6 \cdot 10^{-3}$ m.

Grain size was calculated according to figure 4 based on standard [15].

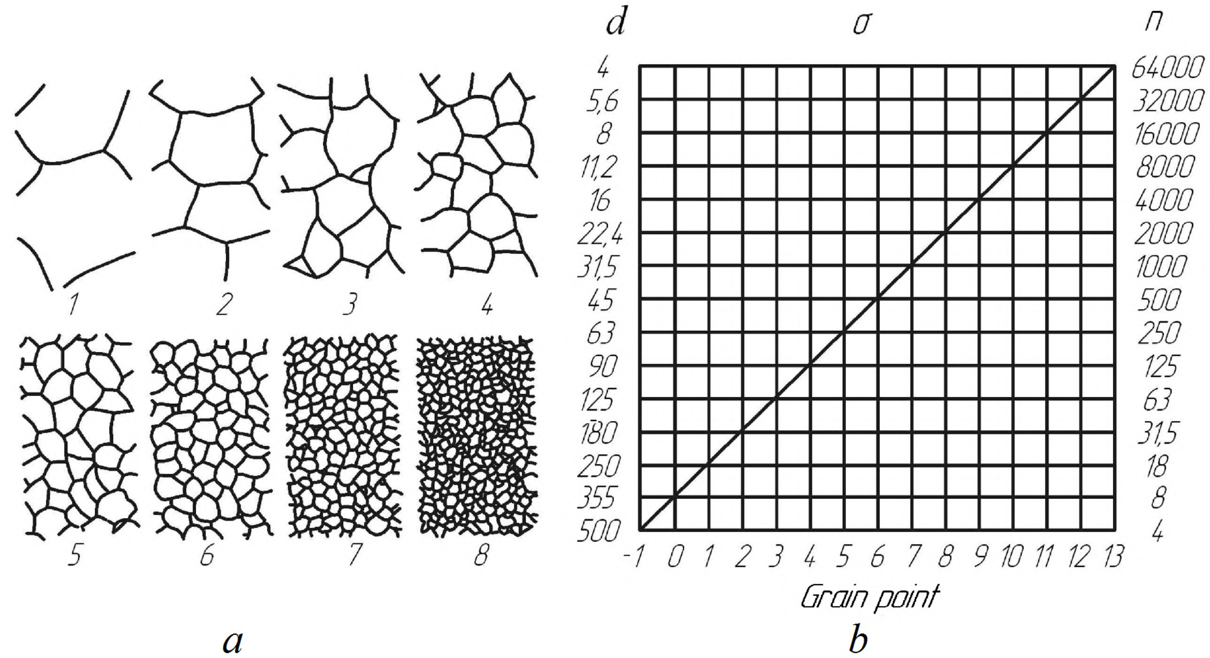

Figure 4. Scale of sizes (a) and nomogram of sizes (b) of grain: 1-8 – points of grains; d – grains size in $m \cdot 10^{-6}$; n – the number of grains per 1 mm^2 [15].

According to Hall-Petch law, yield strength σ_T equals to [16]:

$$\sigma_T = \sigma_0 d + K d_z^{-\frac{1}{2}}, \tag{2}$$

where σ_0 – some stress that is required to slip dislocations (for low-carbon steel $\sigma_0 = 170$ MPa); K – constant that depends on material grade, Hall-Petch coefficient (for calculations $K = 60$ [16]).

Increase of yield strength $\Delta\sigma$ was calculated according to formula: $\Delta\sigma = \sigma_T - \sigma_0$.

Metal yield strength during cold rolling is calculated according to formula:

$$\sigma_T = \sigma_0 + a\varepsilon_\Sigma^n, \tag{3}$$

where a, n – coefficients that take into consideration influence of chemical composition of $a = 33.4$; $n = 0.6$; ε_Σ – summarized deformation degree (in case if rolling is performed in several stages), %.

Deformation degree during study varied from 10 to 80 %.

Deformation degree was determined by the formula [13]:

$$\varepsilon = \frac{\Delta h}{h_0}, \tag{4}$$

where Δh is absolute reduction,

$$\Delta h = h_0 - h_1. \tag{5}$$

Equating formulas (2) and (3), after corresponding transformations, reduction value, which provides specified grain size during cold rolling was determined:

$$\varepsilon = \sqrt[n]{\frac{K/d^{0,5}}{a}} \tag{6}$$

After completing mathematical transformations, we receive dependence of grain size in metal, obtained during rolling, from reduction value:

$$d = \left(\frac{K}{a\varepsilon^n}\right)^2 \tag{7}$$

Offered dependence will enable to adjust grain size changing value of percentage reduction, which determines prospects for controlling steel strength.

5. Results and their explanation

Executed research enabled to identify fraction of intergranular amorphous volume, metal yield strength and its strengthening according to value of reduction during cold rolling. Strengthening value is specified in %. Results of study are presented in table 1.

For more visual observation of changes in amorphous volume fraction, reduction value obtained by formula (3) and metal strengthening value, depending on grain size of internal structure, we draw appropriate graphs (figure 5).

From reference list it is known [17, 18] that fine-grained materials exhibit high plasticity under certain temperature and velocity deformation conditions. Following dependence has been established: the smaller grains size in material is, the more intensive intergranular slipping is developed, and the higher velocity of superplastic deformation and the higher percentage elongation of samples is. These parameters are very important for introduction of technologies that are based on superplasticity effect usage.

Table 1. Parameters of internal structure and properties of steel.

Reduction, %	Grain size, $m \cdot 10^{-6}$	Intergranular surface volume, $(m^3/m^3) \cdot 10^{-3}$	Fraction of intergranular amorphous volume, %	σ_T, MPa	$\Delta\sigma_T$, MPa	Strengthening, %
1.9	355	5.1	0.5	176.8	6.8	4.0
2.6	250	7.2	0.7	178.1	8.1	4.8
4.7	125	10.3	1.0	181.4	11.4	6.7
5.6	100	14.1	1.4	182.8	12.8	7.5
6.2	90	20.4	2.0	183.4	13.4	7.9
11.0	45	40.4	4.1	189.1	19.1	11.2
20.0	22.4	80.8	8.1	197.2	27.2	13.8
26.2	16	116.55	11.7	202.0	32.0	15.8
36.2	11.2	161.55	16.2	206.5	36.5	17.7
47.0	8	233.1	23.3	215.0	45.0	26.5
66.2	5.6	323.1	32.3	217.4	47.4	28.0
83.5	4	466.6	46.7	234.0	64	37.7

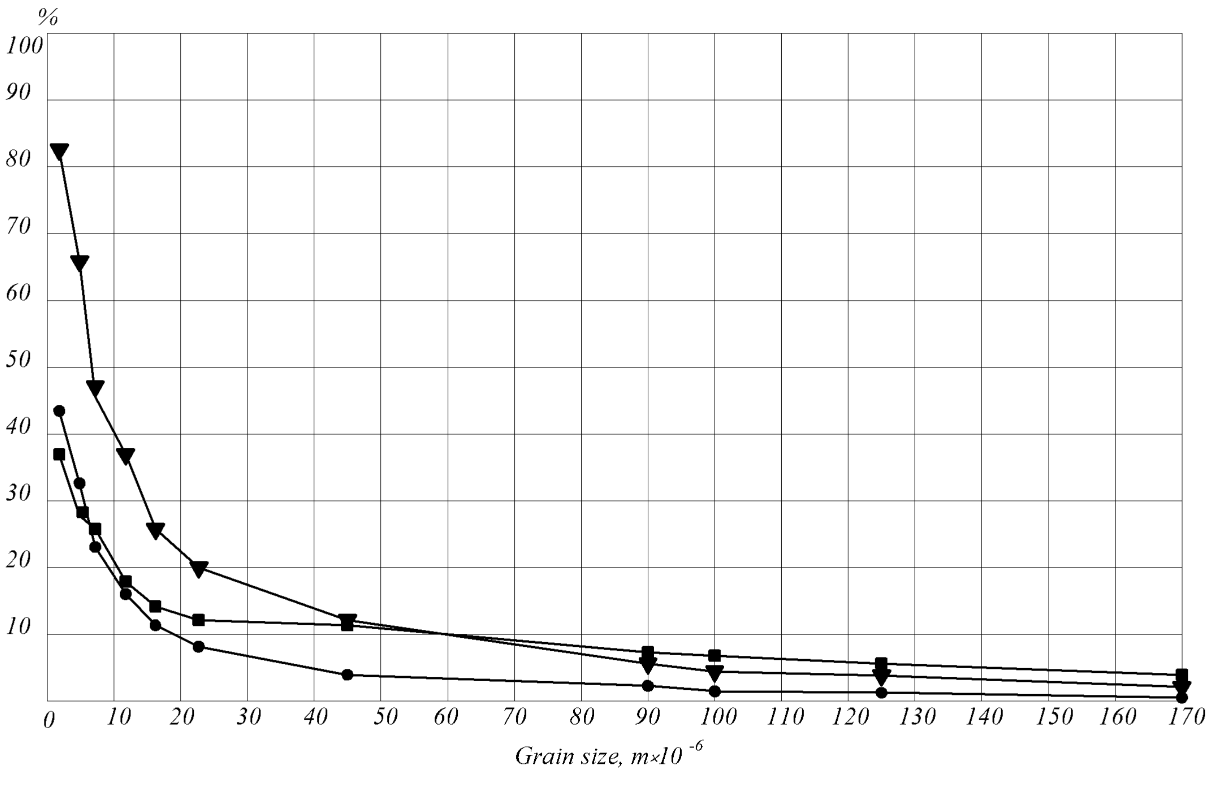

Figure 5. Dependency diagrams of fraction of amorphous volume, strengthening and reduction from grain size: reduction, % (▲); strengthening, % (■); fraction of intergranular amorphous volume, % (●).

During cold rolling, internal properties of treated sheets, i.e. grains size and borders between them, metal yield strength and its changes, can be controlled by reduction value. For this

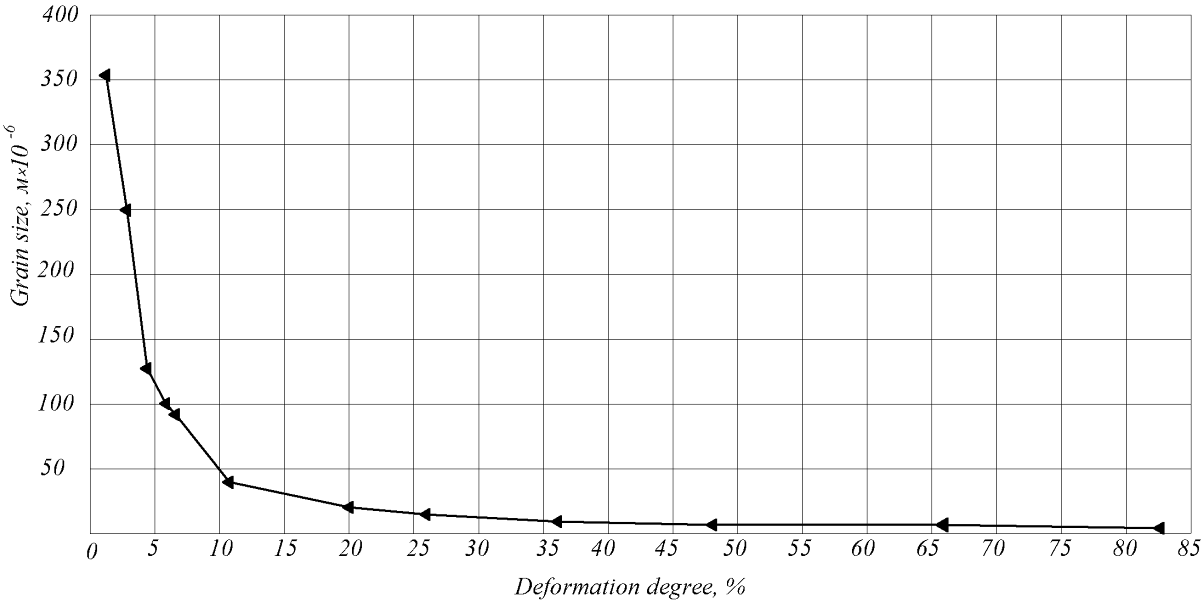

Figure 6. Influence of reduction value on grain size.

purpose, we investigated grain size changes according to formula (7), depending on reduction degree (figure 6).

It shall be noted that grain size decreases with increase in reduction value according to hyperbolic function of n-th order (figure 6). Studies showed that with summarized reduction of more than 80 % during cold rolling, sheets with internal structure having a minimum standard grain size and is characterized with maximum intergranular borders is obtained.

Influence of reduction value to strengthening of metal alloy and fraction of intergranular surface volume is presented in figure 7, where it is clear that these indicators increase almost equally with increased degree of deformation.

Approximation of obtained graphical dependences made it possible to determine that influence of these parameters is performed according to linear function. Studies used least square method, which enabled to obtain following dependencies:

$$line1\varepsilon = 1.8A + 3.7,$$

$$line12\varepsilon = 2.5C - 12.36,$$

where A – fraction of intergranular amorphous volume, %; C – metal strengthening, %.

6. Conclusions

Changes that occur in internal structure of metal products during treatment by pressure were analyzed, it allowed to determine dependencies between metal alloy grains size and borders between them from reduction value during cold rolling.

Regularities of reduction value influence on grains sizes of metal alloy, borders between them and metal strengthening are determined. It is shown that grain size decreases with increase of deformation degree according to hyperbolic function of n-th order, while fraction of intergranular amorphous volume and metal strengthening increase according to linear functions, which enable to control steel strength by adjusting grains size and their joint surface, i.e. changing reduction value.

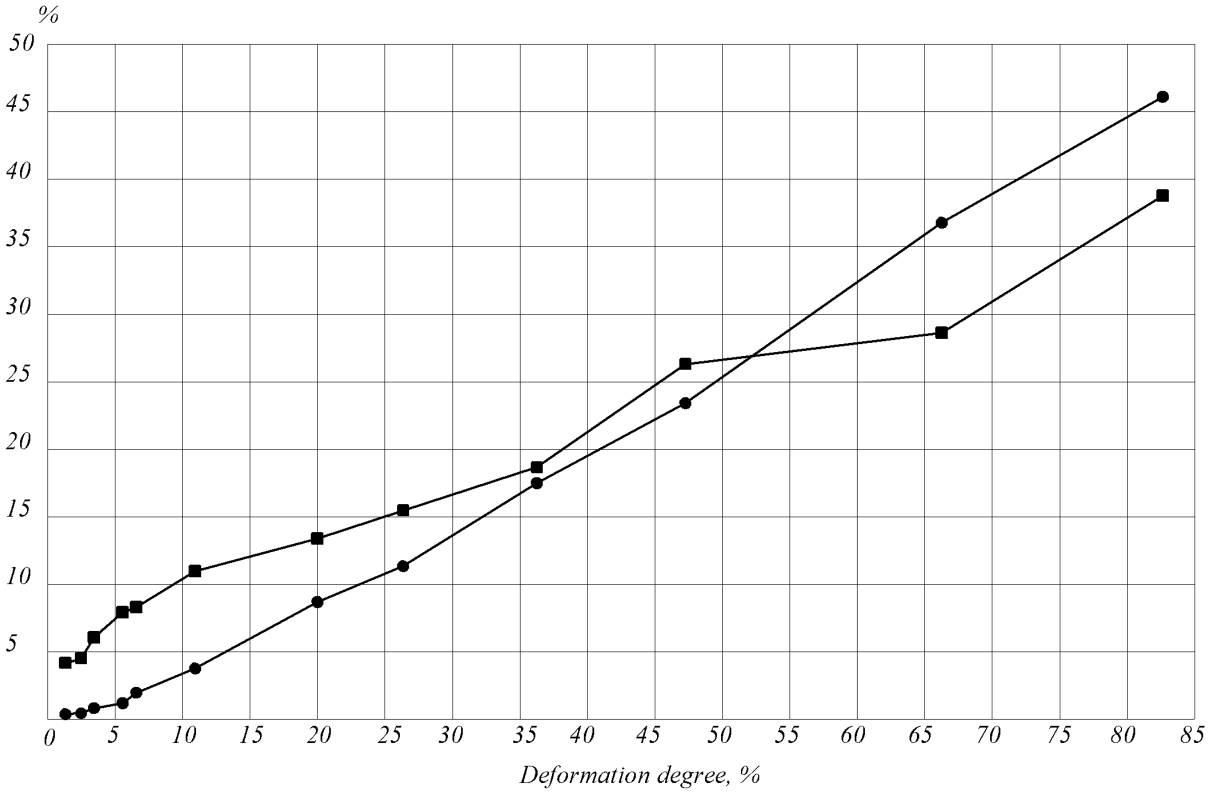

Figure 7. Influence of reduction value on strengthening of metal alloy and fraction of intergranular surface volume: fraction of intergranular amorphous volume, % (●); strengthening, % (■).

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References
[1] Zhbanova O, Saitgareev L, Skidin I, Shapovalova N and Gubin G 2019 Investigation of the influence of electro-impulse current on manganiferous liquid-alloy *Advances in Design, Simulation and Manufacturing* ed Ivanov V, Rong Y, Trojanowska J, Venus J, Liaposhchenko O, Zajac J, Pavlenko I, Edl M and Perakovic D (Cham: Springer International Publishing) pp 207–213 ISBN 978-3-319-93587-4 URL `https://doi.org/10.1007/978-3-319-93587-4_22`
[2] Chubenko V A, Khinotskaya A A, Yarosh T T and Saithareiev L N 2020 *E3S Web of Conferences* **166** URL `https://doi.org/10.1051/e3sconf/202016606009`
[3] Aftandiliants I, Zazymko O and Lopatko K 2013 *Matter Science* (Kyiv: Lira-K, Oldy-plius)
[4] Bylchenko O, Dudka O and Loboda P 2009 *Materials science* (Kyiv: Kondor)
[5] Garnets V and Kovalenko V 2007 *Structural materials science* (Kyiv: Lybid)
[6] Garost A 2010 *Iron-carbon alloys: structure formation and properties* (Minsk: Navuka)
[7] Dziadykevych Y 2009 *Materials in engineering* (Ternopil: Ekonomichna dumka)
[8] Gubenko S and Bolshakov V 2004 *Physical Bases of Plastic Deformation of Metals* (Dnepropetrovsk: PHASA)
[9] Smith W and Hashemi J 2019 *Foundations of Material Science and Engineering* 5th ed (McGraw-Hill)

[10] Kodjaspirov G E, Rudkoy A I and Rybin V V 2010 *Advanced Materials Research* **89-91** 769–772 URL https://doi.org/10.4028/www.scientific.net/AMR.89-91.769
[11] Danchenkoch V, Hrynkevych V and Golovko O 2008 *Theory of metal forming by pressure* (Dnepropetrovsk: Porohy)
[12] Ginzburg V B and Ballas R 2000 *Flat Rolling Fundamentals* (Boca Raton: CRC Press) URL https://doi.org/10.1201/9781482277357
[13] Mazur V L and Nogovitsyn O V 2018 *Theory and Technology of Sheet Rolling: Numerical Analysis and Applications* (Boca Raton: CRC Press) URL https://doi.org/10.1201/9781351173964
[14] Technical Committee for Standardization (TC 4) 2019 *DSTU 8975:2019. Steel. Methods of testing and evaluation of macrostructure* (Kyiv)
[15] Technical Committee for Standardization (TC 4) 2019 *DSTU 8972:2019. Steels and alloys. Methods of detection and determination of grain size* (Kyiv, Ukraine)
[16] Nokhryn A V, Chuvyldeev V N, Kopylov V Y, Lopatyn Yu H Pyrozhnykova O E, V S N, V P A and Kozlova N A 2010 *Bulletin of N.I. Lobachevsky University of Nizhny Novgorod* **5** 142–146 URL http://www.vestnik.unn.ru/ru/nomera?anum=3317
[17] Kaibyshev O A, Valiev R Z and Tsenev N K 1984 *Reports of the Academy of Sciences of the USSR* **278** 93–97
[18] Kaibyshev O, Utyashev F and Hryshchenko S 2002 *Superplasticity, Structure Grinding and Machining of Hard-to-Wear Alloys* (Moscow: Nauka)

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Robust methods for controlling casting processes and the quality of castings

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Abstract. The paper considers the ways of controlling the processes of producing good-quality castings by using robust methods based on the identification of objects under uncertainty, adaptive control methods, stabilization methods for automatic control systems and their mathematical description. The purpose of the paper is to practically elaborate on the task of creating robust technologies for casting based on the study of the stochastic dispersion models of the casting process parameters and to develop a method for stabilizing the casting processes and a method for stabilizing the quality parameters of the castings. The regular patterns of the stochastic dispersion of the casting process parameters were investigated based on the mechanical performance of the casting alloys, their chemical composition, the physical and mechanical properties of the molding mixtures, the dimensions of the castings, and the features of the casting production process such as pouring temperature, element loss during melting and mold hardness. The results of the conducted investigations have shown that to describe the stochastic dispersion of the casting process parameters, it is appropriate to use the Johnson system of distributions. A method for stabilizing the casting quality parameters was developed. It has been shown that it is more efficient to stabilize the strength and improve the dimensional accuracy of the casting simultaneously. With the existing production process, the dimensional accuracy of the casting corresponds to Grade 11 according to GOST 26645-85. With the increase of the dimensional accuracy grade, the metal content of the casting can be reduced by 16.3% after reaching Grade 10, by 20.4% after reaching Grade 9, and by 24.2% after reaching Grade 8.

1. Introduction

When developing the technological process of manufacturing machine parts, there is a need to set up a quality management system for products, the formation of which depends on various phenomena that significantly affect the products performance [1, 2].

Among the processes that affect the quality of machine parts, an important place is taken by the processes related to the production of good-quality castings, which determine their physical and mechanical and performance properties.

Robust methods based on the identification of objects under uncertainty, adaptive control methods, stabilization methods for automatic control systems, mathematical description of the system can be used for this purpose. Currently, there are, mainly in Japanese industry, some striking examples of the use of the concept of robustness to solve practical quality management problems, where the probability of failure of sophisticated products has been reduced from the rate of 1 to 5 failures per one hundred products to one failure per one million products [3, 4].

2. Analysis of literature sources, purpose and objectives

The parameters of the casting processes and the quality of castings consist of two components, deterministic and stochastic. The deterministic component represents the nominal value of the technology parameters, while the stochastic component accounts for the variability of the casting production processes caused by variations in raw material properties, variance and drift in technology and equipment parameters. Variations in product size, structure and properties are the major challenges in creating a perfectly homogeneous industrial production.

Depending on the specific production conditions, both the deterministic and stochastic components can have a decisive effect on the quality of the casting. Therefore, when solving the problem of casting quality control, both components of the technology parameters must be considered quantitatively. However, the case is somewhat different in practice. The Generation 1 casting technologies used at an early stage of development of the casting technology involved a simplified conceptual model of the technology, whereby controlled process parameters were considered as purely deterministic values [5, 6].

Subsequently, an effective solution to the problem of achieving a high level of quality of industrial products, including cast parts, has proved impossible without any quantitative consideration of the statistical component of the technology parameters. Therefore, the industry in developed countries started to use statistical methods in the field of quality control and quality management in the early 20th century. Up-to-date casting methods developed and improved in the 20th century based on a scientific and technological approach can be identified as Generation II technologies [7].

One of the most important conclusions of the statistical theory of quality management is that in order to solve the problem of creating high-quality industrial products, it is necessary not only to consider but also to manage the degree of stochasticity of technological parameters. Within this approach, the concept of new Generation 3 technologies was developed; these were called robust, and their main feature is resilience to random factors.

The stochasticity factor plays a major role in the formation of the consumer and performance properties of cast parts. A specific feature of the casting technology is that the quality parameters are affected by lots of variables, the number of which, according to experts, is estimated to be 2000 to 3000, while only a small number of them, about a few dozen, can be referred to as controllable variables. As a consequence, there is an inevitably wide variation in the quality parameters of the castings. Therefore, the development and practical use of robust technologies is one of the major scientific and practical challenges in the field of casting technology [8].

The analysis of the situation has shown that the existing pattern of technological research established in the field of casting technology should be supplemented by a fundamentally new stage related to the development of an apparatus, methods and working algorithms to address the issue of stabilizing the parameters of the casting process and the quality of castings.

Improving the quality and competitiveness of industrial products inevitably involves additional costs and an increase in their cost price. To find a rational solution to the problem of improving the quality of castings requires the development of a conceptual and mathematical model of the quality formation process, which considers all costs, risks and losses incurred by the designer, manufacturer and consumer of the products [9].

To date, neither general method nor mathematical and algorithmic apparatus for solving the problem of improving the quality and stabilizing the parameters of castings or cast parts has been developed.

The purpose of the research paper is to practically elaborate on the task of creating robust technologies for casting based on the study of the stochastic dispersion models of the casting

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process parameters, and to develop a method for stabilizing the casting technology, and a method for stabilizing the quality parameters of the castings.

3. Method

The primary objective in controlling the reliability of a cast part is to determine the function of distributing the load capacity of the casting. Therefore, the first step in addressing the issue of controlling the reliability is to define the general law of load capacity dispersion.

Engineering problems typically use uniform, normal, and exponential distribution laws. These laws can be used to solve training and elementary tasks, but they are totally inappropriate for solving practical tasks related to the management of the quality of castings [10].

The regular patterns of the stochastic dispersion of the casting process parameters were investigated as follows. A hundred empirical functions obtained by statistical sampling in foundries in automotive and tractor, agricultural, and transport mechanical engineering industries were studied [11,12]. The mechanical performance of the casting alloys, their chemical composition, the physical and mechanical properties of the molding mixtures, the dimensions of the castings, and the features of the casting production process such as pouring temperature, element loss during melting and mold hardness were studied as parameters [13, 14].

To examine the possibility of an adequate description of the distribution functions of the casting process parameters, two currently existing versatile Pearson and Johnson systems of distributions were reviewed.

4. Results and discussion

The results of the conducted investigations have shown that to describe the stochastic dispersion of the casting process parameters, it is appropriate to use the Johnson system of distributions. Its advantages can be summarized as follows:

- the system consists of only three types of functions;
- there are relatively simple methods for the approximate calculation of their parameters;
- the scope of the system is universal.

The Johnson system of distributions includes the equation of three curves referred to as S_l, S_b, S_u families in mathematical statistics. The functions of the S_b family describe the distribution of a random variable whose limits are finite and best meet the nature of the dispersion of the casting technology parameters.

A meaningful analysis of the problem of investigating the regular patterns of random fluctuations of the casting processes was conducted as follows. All parameters of the casting processes cannot by their nature take negative and infinitely large values; therefore, they necessarily have an upper and lower limit.

In view of this, it is necessary to impose a requirement on the functions describing the dispersion of the casting parameters, by which the nature of the distribution function used must be consistent with the nature of the parameter being described. It therefore follows that all functions having at least one infinite limit of variation should be discarded to describe the regular patterns of any parameter of the casting processes and systems.

After filtering all known distribution functions through this requirement, the only remnant of these is the Johnson S_b distribution. It alone has two properties at once: meaningful and mathematical adequacy to solve both technological and problems related to the reliability of cast parts. Thus, the Johnson S_b distribution should become the main function when describing the dispersion patterns of the quality parameters of castings and supersede all others, including the normal distribution law.

One of the key components of the problem of improving the quality of castings is the stabilization of the process properties of molding mixtures [15]. The existing approach to addressing this issue based on the data provided by online control of the properties of the molding mixture is ineffective because control over compactability, moisture contact and strength can be carried out no more often than every 30 to 40 minutes, while control over the content of active bentonite, losses during calcination, particle size distribution no more often than once per shift. In this case, deviation from the set parameters of the mixture preparation technology are detected after its application [16, 17].

To stabilize the casting technology in the in-line production of cast parts for agricultural machinery, the following tasks were solved:

- a method was developed, and production and statistical research was conducted to study the parameters of dispersion of the technological properties of molding mixtures;
- mathematical models of the formation process of properties of molding mixtures were built;
- practical recommendations for improving the technological process of production of castings were developed and implemented.

A specific feature of solving the problem of improving the stability of the process and diagnosing the casting defects is the requirement for increased reliability and accuracy of the production information used [18, 19]. For this purpose, a method of issuing data sheets for castings was developed, based on which industrial experiments were conducted in foundries. The point of the method of issuing data sheets for castings was reduced to perform sequentially the following operations.

The following parameters were monitored and recorded in the melting shop: the quantity, size and chemical composition of charge materials, the melting process parameters, the quantity and composition of deoxidizers and fluxes used, the temperature of the metal in the trough and in the ladle, the poring speed and temperature. In addition, samples were taken from each heat in the steel foundry to determine the gas saturation of the metal [20].

The following operations were performed on the molding and pouring conveyor during the mold-making process:

- the numerical indexes in ascending order were stamped on the horizontal surface of the lower half of the mold;
- each mold was sampled for rapid determination of its properties in the shops express laboratory;
- the hardness of the mold surface was determined using a hardness tester at three points on the mold.

After completing the finishing operations the castings, each with an individual numerical index, were presented to the technical control department to be sorted. The information obtained was consolidated in a single table; the increased validity and reliability of the data obtained is due to the individual determination of all process variables for each casting. The data table was used to solve the tasks of stabilizing the technology parameters, determine the causes of casting defects and the degree of influence of individual variables on the quality and extent of casting rejects.

The solution to the problem of improving the stability of the technological properties of molding mixtures under production conditions was implemented as follows. As the object of research, a unified molding mixture used for the production of carbon steel castings was chosen with the following composition: sand – 89 to 92%; refractory clay – 7.5 to 9.5%; fuel oil – 0.8 to 1.0%. The following requirements were set for the mixture: gas permeability of at least 70 GPU, ultimate strength when wet and water content in the ranges of 0.05 to 0.06 MPa and 4.6

to 5.0%, respectively. The results of 120 data obtained at the facility for the determination of the gas generation value of the mixture were processed, and samples for its determination were collected in the workshop at regular intervals for a month.

The data obtained show that the most important technological properties of the molding mixture, which determine the quality of the mold, are extremely unstable. For example, the extreme values of the dispersion range of gas permeability are 50 and 250 GPU, and those of the gas-generation value are 10 and 65 cm^3/g, i.e. the limit values of the dispersion range differ from each other by 5 to 6.5 times.

It therefore follows that in order to solve the problem of dealing with gas-induced casting defects, it is necessary to reduce fluctuations in the gas permeability and gas-generation value of the molding mixture. The solution of this problem is particularly important for steel foundries, in view of the fact that the surface layers of the mold when in contact with the liquid steel are heated to a high temperature of about 1,100 to 1,200 °C [21, 22].

The major factor reducing the quality of steel castings is that these are prone to having gas-induced casting defects such as blowholes, pinholes, gas and shrinkage porosity. Mathematical modeling methods have been used to quantitatively study the conditions for the formation of gas- and shrinkage-induced defects in castings and to develop measures to prevent these defects.

To build mathematical models of the formation of the process properties of the mixture, the regression models were used, and their parameters were determined based on the experimental data. The investigated dependencies, which were generally non-linear, were used to choose control actions [23, 24].

Based on the results of the conducted research, a method for stabilizing the process of the preparation of a molding mixture was developed, which includes the following sequential procedures:

- implementing 100% acceptance control over all raw materials for the preparation of the molding mixture and systematic monitoring of the gas-generation value of the mixture;
- collecting the most reliable input information based on data sheets of molds and castings;
- improving the accuracy of dosing water and fuel oil in the molding mixture, which are the main sources of gas generation in the mold;
- determining the effect of the mixture preparation process parameters on the gas permeability of the molding mixtures and their correction;
- providing a correlation and regression analysis of the dependence of gas permeability of a mixture on its composition and preparation conditions;
- determining the rational limits of gas permeability and gas-generation value for the examined conditions; adjusting the mixture preparation technology.

According to the conducted investigations, it was found that the lower allowable gas permeability limit for a unified molding mixture in a steel foundry was set at 120 GPU, and the gas-generation upper limit value was set at 28 cm^3/g. The accuracy of dosing of the source components in the preparation of clay suspension was improved; the ongoing control over its density was implemented; the accuracy of dosing when introducing fuel oil was improved, and its dosage was corrected, which was set equal to 0.85 ś 0.05% of the batch in the mixer.

A periodic monitoring of the actual clay content in the mixture was implemented, according to which the amount of clay suspension introduced in the mixture can be adjusted. As a result of this work, the stability of the properties of the molding mixture in the steel foundry has been considerably improved. Specifically, the number of cases of gas permeability below 120 GPU was reduced from 23 to 7%; the range of fluctuations of moisture content in the mixture was reduced from 4.1-5.5% to 4.4-5.2%. While the mean gas-generation value and its root mean square deviation in the initial state were 29.2 and 4.2 cm^3/g, respectively, after implementing the stabilization measures, the values decreased to 26.2 and 2.7 cm^3/g, respectively [25].

Implementing the method for stabilizing the process properties of molding mixtures made it possible to improve the quality of castings and reduce rejects with gas-induced defects.

The third task to be solved in this work is to develop a method for stabilizing the quality parameters of the castings. The method for solving this problem is implemented using the following algorithm.

(i) A mathematical model describing the dependence of the quality parameter Y on the independent technological variables x_1, x_2, , x_n, is built, which can be represented as an equation:
$$Y = f(x_1, x_2, ..., x_n). \tag{1}$$
(ii) The mathematical expectation of the studied parameter is determined. If some of the variables x_i or all of them are random, then the parameter Y is also a random variable, its mathematical expectation can be found by the formula:
$$m_y = f(m_{x_1}, m_{x_2}, ..., m_{x_n}), \tag{2}$$
where m_y, m_{x_i} are the expected values of the parameter y and the variable x_i.

(iii) Determined by the numerical and approximate-analytical method of parameter dispersion Y. For the numerical determination of this quantity, the simulation method can be used. The approximate-analytical method is based on the linearization of the function by expanding it in a Taylor series and preserving the first two terms. In this case, the variance of the parameter Y how the function of the variances of the independents is determined by the formula obtained on the basis of the linearization of the dependence (1):
$$D_y = \sum_{i=1}^{n} \left(\frac{\partial Y}{\partial x_i}\right)^2_{m_{x_i}} D_{x_i}. \tag{3}$$
The index of the partial derivative means that its value is determined by $x_i = m_{x_i}$.

(iv) On the basis of processing the results of industrial experiments, the average values and dispersions of the studied technological variables are determined.

(v) According to formula (3), the variance of the studied quality parameter is determined, the mean values found in the previous paragraph are taken as an estimate of the mathematical expectation of the variables.

(vi) The contribution of each variable to the variance of parameter Y is analyzed, recommendations are developed and implemented to reduce the value of the parameter under study.

The described algorithm was used to stabilize the load capacity of the hinge body part cast of steel 45FL of a T-150K tractor. It was found that the cross-sectional area dispersion and the mechanical property dispersion account for 55% and 45%, respectively to the variation of the load capacity; therefore, the degree of dispersion of these two factors should be reduced. The following measures were developed to improve the geometric accuracy of the part:

- reducing the shrinkage variation by reducing the allowable ranges of pouring temperature and carbon content;
- reducing the deformation of the mold when pouring by improving the strength of the molding mixture and its packing density;

- improving the accuracy of production and assembly of the model elements and centering pins;
- minimizing the assembly clearances between the mold and core pins by optimizing the dimensional chains;
- adjusting the dimensions of the core boxes in view of the deformation of the cores during transportation and drying.

By implementing the above technical measures, the dimensional accuracy of the hinge body casting was improved by 2 to 3 classes according to GOST 26645-85 and the coefficient of variation of the bearing cross-section was reduced from 0.0941 to 0.0402.

To determine whether it is possible to reduce the dispersion of the strength of steel 45FL, a mathematical model of its strength was developed as follows:

$$\sigma = 622 + 2871(C - 0.42) + 182(Si - 0.2) + 128(Mn - 0.45), \tag{4}$$

where C, Si, Mn is the percentage of carbon, silicon and manganese in cast steel.

Based on the processing of the results of the chemical analysis of production heats, it has been found that the dispersion of strength is 2,267.4, and 93% of its value is determined by the variation in the carbon content of steel, 5% by the variation in the silicon content, and 2% by the variation in the manganese content. Therefore, to reduce the dispersion of the mechanical properties of cast steel, it is sufficient to reduce the dispersion of its carbon content. The results of experimental heats showed that by improving the accuracy of dosing admixtures and by improving the express control over the carbon content in steel, the range of its variation can be reduced from 0.09 to 0.07%, and the RMS deviation from 0.015 to 0.01-0.012%. This reduction in the RMS variation made it possible to reduce the dispersion of the ultimate strength of steel and lower the strength dispersion from 2,267.4 to 1,154.7. By reducing the carbon content variation, the minimum tensile strength increased from 540 to 581 MPa, i.e. by 7.6%.

A study of the metal content of the hinge body part showed that while maintaining the guaranteed load capacity of this part equal to 31.2 tons by stabilizing the carbon content and increasing the lower strength value, the mass of the part could be reduced by 7.6%. It is more efficient to stabilize the strength and improve the dimensional accuracy of the casting simultaneously. With the existing production process, the dimensional accuracy of the casting corresponds to Grade 11 according to GOST 26645-85. With the increase of the dimensional accuracy grade, the metal content of the castings can be reduced by 16.3% after reaching Grade 10, by 20.4% after reaching Grade 9, and by 24.2% after reaching Grade 8.

5. Conclusions

1. In the production of good-quality parts, an important role is taken by the processes related to the production of castings, which determine their physical and mechanical and performance properties.
2. Robust methods based on the identification of objects under uncertainty, adaptive control methods, stabilization methods for automatic control systems and mathematical description of the studied processes are promising to manage the quality of castings.
3. The analysis of the situation has shown that the existing pattern of technological research established in the field of casting technology should be supplemented by a fundamentally new stage related to the development of an apparatus, methods and working algorithms to address the issue of stabilizing the parameters of the casting process and the quality of castings.
4. Based on production and statistical research, the regular patterns of the dispersion of the casting process parameters and the quality of castings were studied. It has been shown

that the Johnson Sb distribution is the most appropriate in terms of the meaningfulness and accuracy of describing the variation in the characteristics of technological processes and parameters of castings and cast parts. The obtained results can be used to improve the efficiency of problem solving in the casting quality management systems.

5. To stabilize the casting technology in the in-line production of cast parts for agricultural machinery, the following tasks were solved:
   - a method was developed, and production and statistical research was conducted to study the parameters of dispersion of the technological properties of molding mixtures;
   - mathematical models of the formation process of properties of molding mixtures were built;
   - Practical recommendations for improving the technological process of production of castings were developed and implemented.
6. A method for stabilizing the casting quality parameters was developed. It has been shown that it is more efficient to stabilize the strength and improve the dimensional accuracy of the casting simultaneously. With the existing casting production process, the dimensional accuracy of the casting corresponds to Grade 11 according to GOST 26645-85. With the increase of the dimensional accuracy grade, the metal content of the casting can be reduced by 16.3% after reaching Grade 10, by 20.4% after reaching Grade 9, and by 24.2% after reaching Grade 8.

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References

[1] Abdelkader H 2020 Towards robust production machine learning systems: Managing dataset shift *2020 35th IEEE/ACM International Conference on Automated Software Engineering (ASE)* pp 1164–1166 URL https://ieeexplore.ieee.org/document/9286084

[2] Gyulai D, Kádár B and Monosotori L 2015 *IFAC-PapersOnLine* **48**(3) 2312–2317 ISSN 2405-8963 15th IFAC Symposium onInformation Control Problems inManufacturing URL https://doi.org/10.1016/j.ifacol.2015.06.432

[3] Stricker N, Pfeiffer A, Moser E, Kádár B, Lanza G and Monostori L 2015 *CIRP Annals* **64**(1) 415–418 ISSN 0007-8506 URL https://doi.org/10.1016/j.cirp.2015.04.115

[4] Goetz S, Schleich B and Wartzack S 2020 *Research in Engineering Design* **31**(2) 157–173 ISSN 1435-6066 URL https://doi.org/10.1007/s00163-019-00328-2

[5] Batkovskiy A M, Semenova E G, Fomina A V, Khrustalev E I and Khrustalev O E 2016 *Indian Journal of Science and Technology* **9**(28) 1–11 URL http://doi.org/10.17485/ijst/2016/v9i28/97659

[6] Kuznetsov V P, Kuznetsova S N, Romanovskaya E V, Andryashina N S and Garina E P 2019 Technological Renewal of Industrial Sectors Through Creation of High-tech Industrial Eco-clusters *Ubiquitous Computing and the Internet of Things: Prerequisites for the Development of ICT* ed Popkova E G (Cham: Springer International Publishing) pp 1089–1095 ISBN 978-3-030-13397-9 URL https://doi.org/10.1007/978-3-030-13397-9_112

[7] Potashnik Y S, Garina E P, Romanovskaya E V, Garin A P and Tsymbalov S D 2018 Determining the Value of Own Investment Capital of Industrial Enterprises *The Impact of Information on Modern Humans* ed Popkova E G (Cham: Springer International Publishing) pp 170–178 ISBN 978-3-319-75383-6 URL http://doi.org/10.1007/978-3-319-75383-6_22

[8] Kuznetsov V P, Garina E P, Romanovskaya E V, Kuznetsova S N and Andryashina N S 2018 *Espacios* **39**(1) 25 URL https://www.revistaespacios.com/a18v39n01/a18v39n01p25.pdf

[9] Mizikovsky I E, Druzhilovskaya T Y, Druzhilovskaya E S, Garina E P and Romanovskaya E V 2018 Accounting for Costs and Expenses: Problems of Theory and Practice *The Impact of Information on Modern Humans* ed Popkova E G (Cham: Springer International Publishing) pp 152–162 ISBN 978-3-319-75383-6 URL http://doi.org/10.1007/978-3-319-75383-6_20
[10] Goldstein M L, Morris S A and Yen G G 2004 *The European Physical Journal B - Condensed Matter and Complex Systems* **41**(2) 255–258 ISSN 1434-6036 URL https://doi.org/10.1140/epjb/e2004-00316-5
[11] Pashkov S V and Zelepugin S A 2022 *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science* **236**(21) 10681–10689 URL https://doi.org/10.1177/0954406220939116
[12] Mironenko V V, Polyakova O E, Sechkarenko D A and Kotov V V 2016 *Metallurgist* **59**(9) 871–876 ISSN 1573-8892 URL https://doi.org/10.1007/s11015-016-0186-x
[13] Tschuchnigg F, Schweiger H and Sloan S 2015 *Computers and Geotechnics* **70** 169–177 ISSN 0266-352X URL https://doi.org/10.1016/j.compgeo.2015.06.018
[14] Coogan T J and Kazmer D O 2020 *Additive Manufacturing* **35** 101368 ISSN 2214-8604 URL https://doi.org/10.1016/j.addma.2020.101368
[15] Ponomarenko O, Yevtushenko N, Berlizieva T, Grimzin I and Lysenko T 2023 A Method for Calculating the Strength Performance of Cast Parts *Advanced Manufacturing Processes IV* ed Tonkonogyi V, Ivanov V, Trojanowska J, Oborskyi G and Pavlenko I (Cham: Springer International Publishing) pp 473–481 ISBN 978-3-031-16651-8 URL http://doi.org/10.1007/978-3-031-16651-8_45
[16] Huminski Y Y and Rovin S L 2019 *Foundry Production and Metallurgy* **3** 4145 URL https://doi.org/10.21122/1683-6065-2019-3-41-45
[17] Kuchkorov L A, Alimukhamedov S P, Tursunov N K, Nurmetov K I and Azimov S J 2022 *Texas Journal of Engineering and Technology* **8** 161–167 URL https://zienjournals.com/index.php/tjet/article/view/1829
[18] Venkat S T, Vinod T and Sowmya G 2017 *International Journal of Scientific Research in Science, Engineering and Technology* **3**(2) 463–468 URL https://www.academia.edu/33109550/A_Critical_Review_on_Casting_Types_and_Defects
[19] Li T, Davies J M T and Zhu X 2022 *Journal of Magnesium and Alloys* **10**(1) 129–145 ISSN 2213-9567 URL https://doi.org/10.1016/j.jma.2021.07.005
[20] Chokkalingam B, Priya M, Immanual R and Varun B 2022 *Journal of Advanced Manufacturing Systems* **21**(02) 367–392 URL https://doi.org/10.1142/S0219686722500081
[21] Cao L, Liao D, Sun F, Chen T, Teng Z and Tang Y 2018 *The International Journal of Advanced Manufacturing Technology* **94**(1) 807–815 ISSN 1433-3015 URL https://doi.org/10.1007/s00170-017-0926-5
[22] Zhao J, Zhang Z y, Liu S b, Shi K, Bao C l, Ning Z s, Yan P, Wang L and Lou Y c 2020 *China Foundry* **17**(1) 29–34 ISSN 2365-9459 URL https://doi.org/10.1007/s41230-020-8151-5
[23] Ananthapadmanaban D and Karthik A 2019 Development of an Expert System to Monitor Casting Defects in Foundries *Advances in Manufacturing Processes* ed Vijay Sekar K S, Gupta M and Arockiarajan A (Singapore: Springer Singapore) pp 101–109 ISBN 978-981-13-1724-8 URL https://doi.org/10.1007/978-981-13-1724-8_10
[24] Chen S, Zhang J, Xu K and Xu Q 2020 *Mathematical Problems in Engineering* **2020** 8121276 URL https://doi.org/10.1155/2020/8121276
[25] Berlizieva T, Ponomarenko O, Grimzin I, Yevtushenko N and Khoroshylov O 2022 Control of the Physical and Mechanical Properties of Mixtures Based on Liquid Glass with Various Fillers *Advances in Design, Simulation and Manufacturing V* ed Ivanov V, Trojanowska J, Pavlenko I, Rauch E and Peraković D (Cham: Springer International Publishing) pp 367–374 ISBN 978-3-031-06025-0 URL http://doi.org/10.1007/978-3-031-06025-0_36

Technology of forming a wear-resistant thermite alloy layer based on the Fe-Cr-C system by self-propagating high-temperature synthesis

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Technology of forming a wear-resistant thermite alloy layer based on the Fe-Cr-C system by self-propagating high-temperature synthesis

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Abstract. The technology of forming a thermite alloy layer on the basis of Fe-Cr-C system on a metal basis by self-propagating high-temperature synthesis is offered, which allows to obtain cast functionallayers withphysico-mechanical and exploitativeproperties. The optimal technological parameters of the forming a wear-resistant layer of thermite alloy process are determined: the amount of metal filler with the maximum yield of suitable alloy, the heating temperature of the thermite charge and the mold to obtain additional heat, the temperature ranges of the melt to melt the metal base with further formation of the functional layer. Metallographic studies of the obtained wear-resistant layer of thermite allo[y showed that the zone of formation of the functional layer is characterized by the stability of the macrostructure and the positive effect of non-metallic inclusions in the form of Al_2O_3, which influences the formation of chromium carbides in the obtained alloy by creating the effect of inoculative modification of thermite alloy.

1. Introduction

In foundry production, the “classic” (basic) technology for obtaining a liquid melt which is poured into the mold is metal smelting in a steelmaking unit (for example, in an arc steelmaking or induction furnaces) [1, 2]. Overheating of the obtained metal is not allowed primarily due to increased wear of the furnace lining and increased soot of the alloying elements. It is known that it is optimal to pour molten metal into a mold with a temperature close to the crystallization temperature, but even so it is not possible to obtain two-layer bimetallic castings due to the lack of a quality zone for the formation of functional layers [3–5]. That is why the use of self-propagating high-temperature synthesis (SHS) to form a wear-resistant layer of thermite alloy on a metal basis can be a cost-effective alternative for the production of bimetallic products.

The main physical parameters of the SHS process are the maximum combustion temperature at the level of 8004000 °C and the linear combustion rate of 1-150 mm/s. The combustion process consists of two main stages: reduction of oxides with the formation of metal (metallothermic stage) and the stage of direct synthesis of elements [6].

The mechanism of structure formation and product formation in self-propagating thermite reactions is described in Orrù et al [7–9]. In order to obtain a dense SHS material with high physical and mechanical characteristics, it is necessary to take into account the patterns of the reaction mixture combustion, the formation of chemical and phase compositions of the final product, the crystallization behavior of the alloy [10].

A general overview of thermite reactions, which are exothermic redox reactions involving metal and oxide, is presented by Wang et al [11]. Scientists have presented theoretical and experimental results related to ignition and combustion in self-propagating high-temperature synthesis.

In [6] the technology of materials synthesis based on combined (self-propagating high-temperature synthesis plus metallothermy) processes is described. The author considers theoretical issues of synthesis and technological features of running the combined processesfor micro fusion conditions. Reactions based on the proposed charge compositions led to the synthesis of carbidosteels, which contained a binder component and high-speed steel, and a base tungsten carbides. The parameters of carbide steel yield from the charge were experimentally established, and the microstructure, features of chemical composition, mechanical and technological properties were investigated for the synthesized alloys.

The issue of synthesis of steels and cast irons by metallothermy is considered in more detail in [12]. In particular, the synthesis of different types of steels: heat-resistant, tool, spring and others, as well as different types of cast iron: grey, white and high-strength. The author shows that the mechanical properties of thermite steels are better than those of industrial analogues and reveals the influence of the metallothermic method of synthesis on the features of the microstructure and phase composition of thermite steels. Theoretical and experimental studies have also shown the possibility of using thermite cast irons not only to obtain castings, but also for thermite welding technology.

In [13] the results of experimental and theoretical studies of the combustion of iron-aluminum thermite mixtures for iron and composites based on ironwas given. The effect of granulation and addition of flux on the combustion process, composition and structure of final products was evaluated. The author proposed a method of burning thermite mixture with bottom ignition and a model of a combustion plant. Also, the results of research on the combustion of granular thermite mixture are given in [14, 15].

The study of Coffey et al [16] is devoted to the use of additives and fluxes in metallothermicprocesses in self-propagating high-temperature synthesis.

Lonsdale [17] presents an overview of the features of thermite welding rails, and in particular, the practical and technical advantages and disadvantages of welding and focuses on improving the quality of thermite welding. Welding aspects of railway connections by means of thermite welding or aluminothermic welding are also considered in [18].

The research of the obtaining steelcomposites of the Fe-TiC system using aluminum thermic reactions of the SHS process possibility are presented in the study [19].

The work of Yeh and Wang [20], which considers the effect of stoichiometry on the formation of intermetallic compounds of the Nb-Al type is also of particular interest. The authors investigated the production of various niobium aluminides (such as Nb_3Al, Nb_2Al and $NbAl_3$) using extruded samples from Al and Nb_2O_5 powder mixtures using the SHS process.

The study by Sereda et al [21] is devoted to the thermodynamic analysis of reactions possible in the production of intermetallic nickel-aluminum alloys in high-temperature synthesis. Thermodynamic analysis showed that for the nickel-aluminum system, the adiabatic combustion temperature is at the level of the melting point of the final product such as intermetallic one, which is the sufficient condition for the SHS reaction under normal conditions.

We should note the scientific achievements of Sereda et al [22], which considered modelling of production processes of alloys based on TiAl and NiAl in the SHS process.

The work of Belokon and Belokon [23] is devoted to the study of the regularities of high-temperature synthesis of intermetallic compounds, in particular Ti-Al, and it is shown that the synthesis of metals and alloys based on them can take place under conditions of thermal explosion. The compositions of SHS mixtures and technological modes of self-propagating high-temperature synthesis proposed by the authors allow to create intermetallic alloys based on titanium aluminides.

Therefore, there is reason to believe that the issue of determining the optimal technological parameters of the process of forming a wear-resistant layer of thermite alloy based on the Fe-Cr-C system has not been given sufficient attention. This area of research is quite relevant in the production of bimetallic products.

2. Materials and methods

When considering the technology of forming a layer of thermite alloy based on the Fe-Cr-C system on a metal basis using the SHS process, next materials were used as components of the charge (table 1): scale, aluminum powder of the PA-2 brand (GOST 6058-73) with the fraction of 45 μm, iron powder of the PZHRV 2.300.28 brand (GOST 9849-86) with the fraction below 300 μm, chromium powder of the PHA brand (GOST 14-00186482-051-2005) with the fraction of 300 μm and carburetor in the form of a modifier by MK91A brand with the fraction up to 5 mm. Calcification of rolled scale to remove grease and oxidation was performed in a muffle furnace SNOL 7.2/900 at a temperature of 600 °C for 30 min.

Table 1. The composition of the charge for forming a layer of thermite alloy.

Batch composition, kg	Batch 1	Batch 2
Cinder	100,00	100,00
Iron powder of the PZHRV brand 2.300.28	45,64	–
PA-2 aluminum powder	30,00	30,00
PHA chromium powder	–	16,60
MK91A brand modifier	8,90	6,30

The study of the process of a thermite alloy surfacing on a metal base was carried out in a mold consisting of a sand-clay shell with a lid (figure 1).

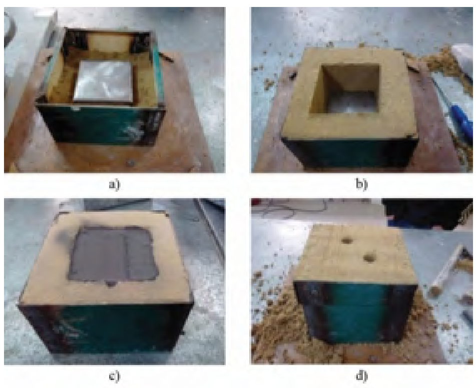


Figure 1. Experimental mold: (a) installation of a metal basis in the form on model; (b) sand-clay form with a cavity for thermite charge; (c) compacted thermite mixture in the form; (d) form assembled with a hole for burning thermites and gas removal.

To remove moisture, the mold was subjected to a drying process at a temperature of 524 K for 1.5 hours. To control the temperature, four tungsten-rhenium thermocouples were installed in the mold (figure 2). Sealing of the thermite alloy was performed on a vibrating table.

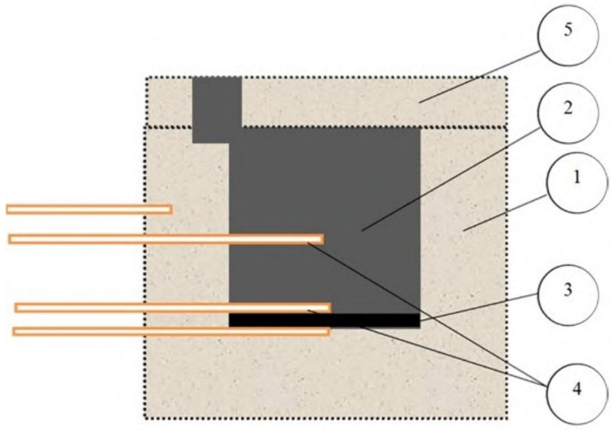


Figure 2. Scheme of experimental mold: 1 molding mixture; 2 thermite mixture; 3 metal base; 4 thermite charge; 5 lid of the mold.

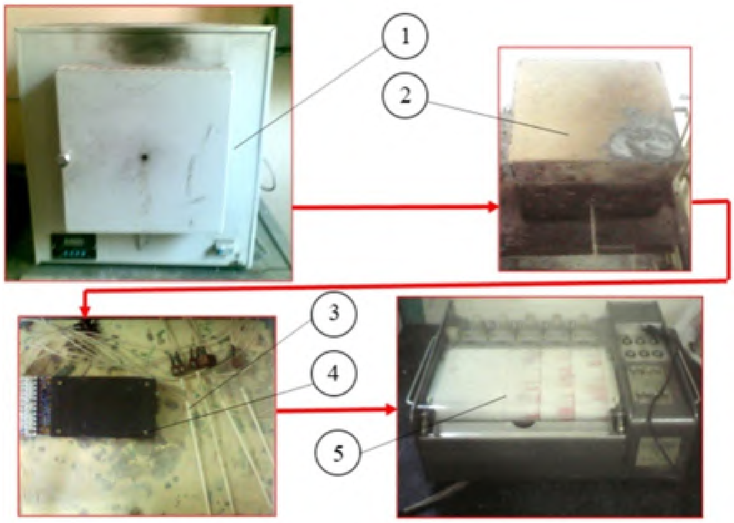
To study the kinetics of thermal processes occurring in the mold during the formation of a layer of thermite alloy during the SHS process, an experimental laboratory setup was additionally developed (figure 3). The temperature measurement range lasted from the moment of ignition of the thermite charge (873 K) to the temperature of the combustion wave of the thermite charge (2774 K). Thermocouples were insulated with ceramic tubes with two holes with a diameter of 0.3 mm and connected to a high-speed self-recording device H 32-4.

3. Results and discussion

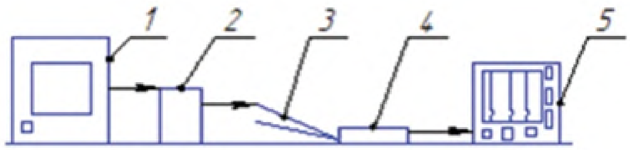
In the study of the influence of the mold heating time on the change in temperature, the prepared mold was heated in a preheated to 873 K laboratory muffle furnace SNOL 7.2/900. The data in figure 4 show that the temperature of the mold wall, after installing it in the oven, increases rapidly to 873 K. During the first 40 min the rate of temperature rise is 13.5 K/min and gradually decreases to 3.7 K/min in the heating time range from 40 min to 80 min. Upon further finding the form in the furnace, the heating rate increases at a rate of 5.3 K/min.

To accelerate the heating time of the mold with direct contact of open surfaces with the heated atmosphere of the furnace, a mold with an open metal base in the lower part was made (figure 5). The use of this design has reduced the heating time of the mold from 120 min up to 90 min. However, it should be noted that the open surface of the metal base in the lower part of the mold makes significant changes in the course of self-propagating high-temperature synthesis. After initiating the combustion of the thermite mixture, for 0.5 min from the beginning of the process, there is a sharp decrease in the temperature of the lower surface of the metal base to the ambient temperature (4-5 °C), which persists for 3.5-4 sec (figure 6, curve 1).

Analysis of these thermocouples installed on the upper surface of the metal base (figure 6, curve 2) showed that the total combustion time of the thermite charge is 8.5 sec, where the combustion front reaches the surface of the metal base and its temperature for 1 sec, rapidly increases to 2024-2054 K, which indicates the beginning of the formation of a thermite alloy. This temperature is maintained for 5-7 sec, which contributes to the fusion of the liquid phase and the metal base. At 15.5 sec from the beginning of the process, the temperature of the formed layer decreases to the temperature of crystallization of iron, and the tendency to decrease the temperature is observed up to the 20th sec.



a



b

Figure 3. General view (a) and scheme (b) of the experimental laboratory installation for studying the kinetics of thermal processes: 1 laboratory muffle furnace; 2 experimental form assembled with thermocouples; 3 tungsten-rhenium thermocouples BP 5/20; 4 signal amplifier thermocouples with compensates; 5 high-speed self-recording device H32-4.

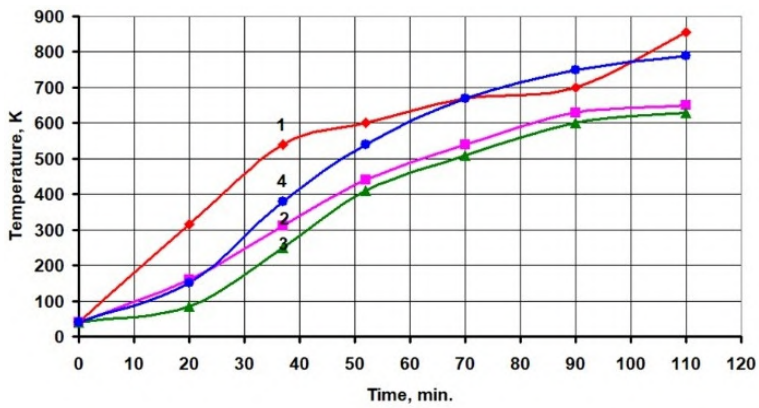


Figure 4. Influence of time of heating of a mold on change of temperature: 1 heating of a wall of a form; 2 heating under the plate; 3 heating of the thermite charge over the plate; 4 heating of the thermite charge in the middle of the mold.

Studies of the temperature behavior of the molding mixture (figure 6, curve 3) showed an initial rapid (within 0.5-1 sec) decrease in temperature from 873 K to 723 K, but with its subsequent increase at a speed of 284-286 K/sec for the next 10 sec. The tendency to maintain

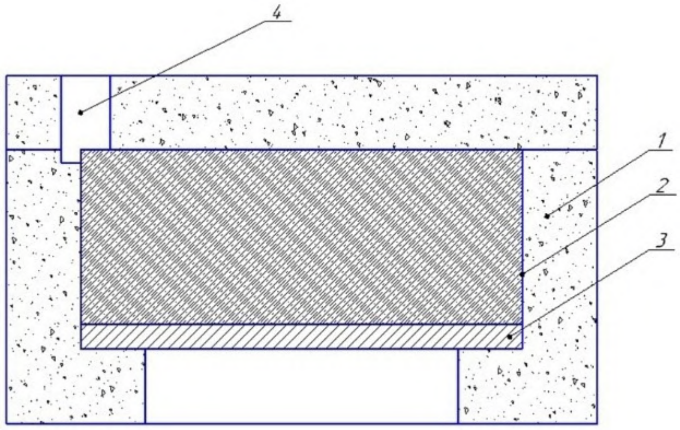


Figure 5. Foundry mold with an open metal base in the lower part: 1 molding mixture; 2 thermite charge; 3 metal base; 4 hole for igniting the thermite charge and exhaust gases.

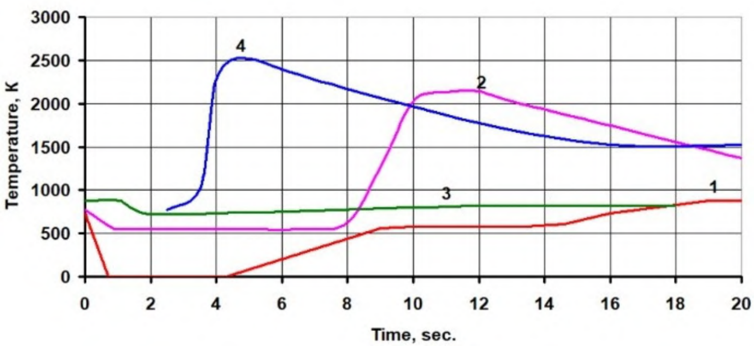


Figure 6. The effect of heating time of the mold with an open metal base in the lower part on the temperature change: 1 the lower surface of the metal base; 2 the upper surface of the metal base; 3 molding mixture; 4 temperature of the working medium thermite; charge-thermite alloy.

the temperature at 823 K must be preserved till complete crystallization of the metal.

The process of burning thermites takes place at a temperature of 3100-3200 K, which exceeds the boiling point of iron. This, in turn, allows you to add to the charge of the metal filler in such a volume that the temperature of the melt to form a functional layer was not lower than 2474-2674 K (figure 6, curve 4).

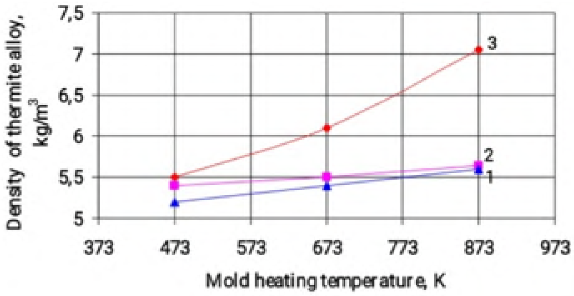
It should be noted that the open metal base in the lower part of the mold accelerates the preheating of the mold in the muffle furnace, but on the other hand there is also cooling of both the molding mixture and the metal base after firing the thermite charge. Thus, the analysis of thermo-grams from thermocouples of the mold shows that for 20 sec depending on the location of the thermocouple, there is an abrupt fluctuation of the temperature behavior.

When determining the optimal technological parameters of the process of forming a wear-resistant layer of thermite alloy based on the Fe-Cr-C system during SHS process, it was noted that the temperature of the thermite alloy after the combustion wave should not exceed the boiling point of iron, and the lower temperature limit of thermite alloy should exceed crystallization of the alloy not less than 1000 °C. The increase in the temperature of the thermite alloy directly depends on both the preheating of the mold and the amount of metal filler in the thermite charge. It should be borne in mind that the introduction of a very large amount of metal filler reduces the yield of a suitable thermite alloy. Therefore, the optimal content of metal filler in the thermite charge heated to 873 K is a composition of 40%.

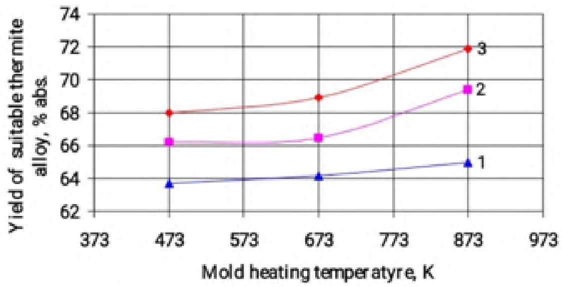
It was experimentally determined that the mass of the formed wear-resistant layer of thermite alloy obtained from the charge 1 and the charge 2 was 97.94 kg and 68.9 kg, respectively.

The obtained samples of thermite alloy were investigated for structural properties such as density in accordance with GOST 20018-74, porosity in accordance with GOST 9391-80, and macro-structure evaluation in accordance with GOST 10243-75.

So in (figure 7, a) the dependence of the density of the thermite alloy on the heating temperature of the mold and the content of the metal filler is showed.



a



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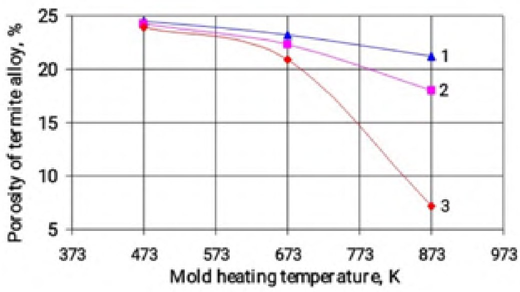


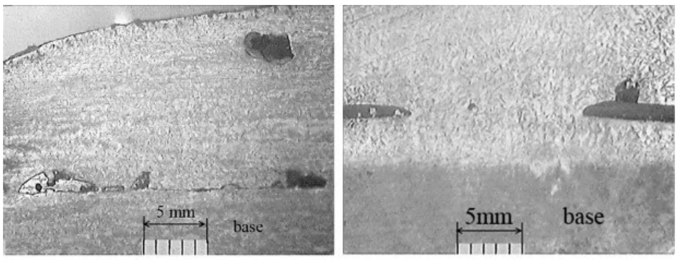
c

Figure 7. Dependence of density (a), yield of suitable (b) and porosity (c) of thermite alloy on heating temperature of mold and content of metal filler: from 1 to 20% of metal filler; from 2 to 30% of metal filler; from 3 to 40% of metal filler.

It is shown that increasing the amount of metal filler in the charge from 20% to 40%, when heating the mold to 873 K, increases the yield of suitable thermite alloy to 71.9% by weight of the original charge (figure 7, b) and it increases the density to 7.05 kg/m^3. Increasing the amount of metal filler to 40% and it also reduces the porosity of the formed thermite alloy to 5.5% (figure 7, c).

Metallographic studies of the samples of the obtained wear-resistant layer were performed in order to analyze the influence of the heating temperature of the mold on the process of formation of macrostructure defects in the zone of formation of functional layers. Metal graphic studies of samples of the mixture based on chromium (charge 2) were performed on an optical horizontal microscope of MIM-8 brand (light field mode). The samples were pre-cut at the level of the part by a water-cooled abrasive cutting wheel. When studying the quality of the connection of functional layers and analysis of structure formation, the samples were ground on the surface, baited on the macrostructure by electrical chemical etching in a saturated solution of ferric chloride (cathode a plate of corrosion-resistant steel).

In metal graphic studies of the formation zone of the thermite alloy layer based on the Fe-Cr-C system with a metal base at a heating temperature of the mold below 473 K, there was a loose connection of layers with the base, there were inclusions of slag, and in the upper part there were shrinkage shells (figure 8, a).



a b

Figure 8. Metal graphic studies of the formed wear-resistant layer of thermite alloy based on the Fe-Cr-C system: (a) when heating the mold to 473 K; (b) when heating the mold to 873 K.

Layered, perpendicular and elongated crystallization (movement of the crystallization front in the form of terraces parallel to the crystal surface) was observed in the formed layer of thermite alloy.

In the analysis of samples obtained by heating the mold to 673 K, in the zone of formation of functional layers, a line of discontinuities was observed, the metal base was not welded, because the aluminum thermic reaction products did not float to the alloy surface due to rapid cooling of the thermite alloy layer.

For samples obtained by heating the mold to 873 K, the liquid state of the thermite alloy was longer, the time to crystallization was 16 sec. The surface of the metal base melted, and the slag consisting of Al_2O_3 (corundum) emerged from the zone of formation of the functional layer (figure 8, b) [24]

Thus, the zone of formation of the functional layer is characterized by the stability of the macrostructure and the positive effect of corundum, which, creating the effect of inoculating modification of the thermite alloy, in turn contributes to the formation of chromium carbides.

Thus, the result of the proposed technology of forming a layer of thermite alloy based on Fe-Cr-C system by self-propagating high-temperature synthesis are obtained samples of thermite alloy, on the surface of which when the mold is heated to 873 K in the slag phase metal inclusions are formed in separate spherical shape (figure 9).

This is due to the rapid stage of combustion and is accompanied by intense spraying of the resulting synthesized metal. The results of the study of adding to the thermite charge a 40% of the metal filler when heating the mold to 873 K are presented in (figure 10).

When the thermite charge contains more than 40% of metal filler, regardless of the heating temperature of the mold, there is a decrease in melt temperature, which leads to its significant porosity, as well as the presence of oxidized areas in the joint that did not melt (figure 11).

Figure 9. Samples of the formed layer of thermite alloy obtained by SHS process (heating of the mold to 873 K) with different amounts of metal filler: (a) 20% metal filler; (b) 30% metal filler.

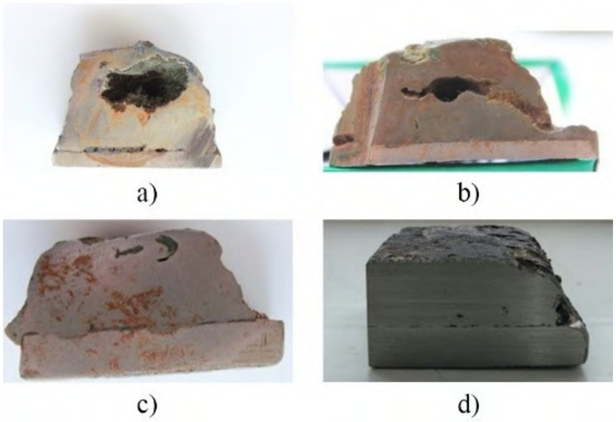


Figure 10. Section of samples of the formed layer of thermite alloy obtained by SHS process (40% metal filler) at different heating temperatures of the mold: (a) without heating; (b) when heated to 473 K; (c) when heated to 673 K; (d) when heated to 873 K.

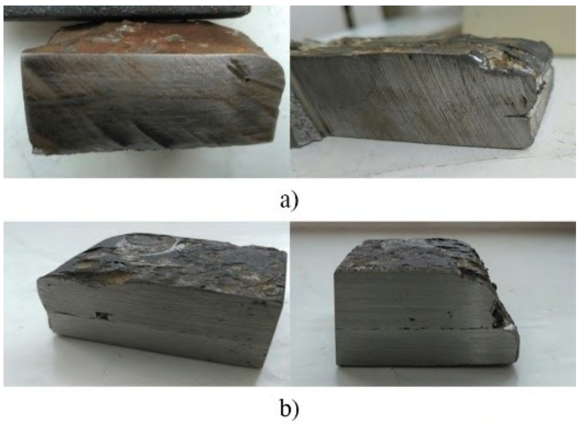


Figure 11. Section of samples of the formed layer of thermite alloy obtained by SHS process when heating the mold to 873K: (a) samples with 40% metal filler; (b) samples with more than 40% metallic filler.

4. Conclusions

The technology of forming a thermite alloy layer on the basis of the Fe-Cr-C system on a metal basis by SHS process is offered, which allows to obtain cast functional layers with improved physical and mechanical, and operational properties. It is shown that the use of open mold in the lower part for the needs of foundry production has a negative effect on the SHS process and maintaining the temperature of the metal base, which is associated primarily with the flow of air from the environment in the lower cavity of the mold due to reactive jet of gas released from the mold through the outlet in the lid during the combustion of the thermite mixture.

The optimal technological parameters of the process of forming a wear-resistant thermite alloy layer are determined: the amount of metal filler with the maximum yield of suitable alloy, the heating temperature behavior of the thermite charge and the casting mold to obtain additional heat, the temperature ranges of the melt to melt the metal base. It is established that the optimal amount of metal filler in the mold, heated up to 873 K for the formation of a wear-resistant layer of thermite alloy is 40%. It is shown that increasing the amount of metal filler from 20% to 40% affects the structural properties of the formed layer of thermite alloy: increases the density of the alloy by 33% and decreases porosity of the alloy by 17.3%, while the yield of suitable thermite alloy increases to 71.9 absolute percent. It should be noted that lowering the heating temperature of the mold below 873 K degrades the quality of the formed layer of thermite alloy: thermite alloy does not separate from the slag and is released into separate spherical formations.

Metallographic studies of the obtained wear-resistant layer of thermite alloy penetrating into the metal base to a depth of 3 mm showed that the zone of functional layer formation is characterized by macrostructure stability and positive effect of corundum (as a residue of aluminothermic reaction product) in the obtained alloy. In this case, non-metal inclusions in the form of corundum, creating the effect of inoculating modification of the thermite alloy, in turn contribute to the formation of chromium carbides.

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References

[1] Kudrin V A 2003 *Theory and technology of steel production* (Moscow: Mir)
[2] Verkhovlyuk A M, Narivskiy A V and Mogitalenko V G 2016 *Technology of metal and alloy production for live wire production* (Kiev: Vinichenko)
[3] Campbell J 2003 *Castings* 2nd ed (Butterworth-Heinemann)
[4] Beeley P 2001 *Foundry Technology* 2nd ed (Butterworth-Heinemann)
[5] Chastain S 2003 *Metal Casting: A Sand Casting Manual for the Small Foundry* (Jacksonville: Chastain Publishing)
[6] Zhyhuts Y I 2004 *Scientific Bulletin of Uzhhorod University: Physics series* **15** 101 – 112
[7] Orrù R, Simoncini B, Virdis P F and Cao G 1998 *Chemical Engineering Communications* **163**(1) 23–35 URL https://doi.org/10.1080/00986449808912342
[8] Orrù R, Simoncini B, Virdis P F and Cao G 1997 *Metallurgical Science and Technology* **15**(1) 31–38 URL https://www.fracturae.com/index.php/MST/article/view/1026
[9] Orrù R, Simoncini B, Virdis P F and Cao G 1998 *Chemical Engineering Communication* **163**(1) 23–36 URL https://doi.org/10.1080/00986449808912342
[10] Evtushenko A T, Pazare S and Torbunov S S 2007 *Metal Science and Heat Treatment* **49**(3) 200–203 ISSN 1573-8973 URL https://doi.org/10.1007/s11041-007-0036-3
[11] Wang L L, Munir Z A and Maximov Y M 1993 *Journal of Materials Science* **28** 3693–3708 ISSN 1573-4803 URL https://doi.org/10.1007/BF00353167
[12] Zhiguts Y Y 2008 *Alloys synthesized by metal thermy and SHS processes* (Uzhhorod)
[13] Yatsenko V V 2011 *Combustion of granular iron-aluminum thermite mixture in the production of iron and its composite with titanium carbide* Ph.D. thesis Samara

[14] Amosov A P, Makarenko A G, Samboruk A R, Seplyarskii B S, Samboruk A A, Gerasimov I O, Orlov A V and Yatsenko V V 2009 Effect of batch pelletizing on realization of SHS processes *X International Symposium on Self-propagating High-Temperature Synthesis: Book of Abstracts* (Tsakhkadzor) pp 127–128

[15] Amosov A P, Makarenko A G, Samboruk A R, Seplyarskii B S, Samboruk A A, Gerasimov I O, Orlov A V and Yatsenko V V 2013 *Russian Journal of Non-Ferrous Metals* **54**(3) 267–273 ISSN 1934-970X URL https://doi.org/10.3103/S1067821213030024

[16] Coffey B, Schropp, Jr D R and Kwiatkowski K C 2009 Solid-state thermite composition based heating device Patent US20100252022A1 URL https://patents.google.com/patent/US20100252022A1/en

[17] Lonsdale C P 1999 Thermite rail welding: History, process developments, current practices and outlook for the 21st century *Proc. of the AREMA 1999 annual conf, The American railway engineering and maintenance-of-way association* pp 2–5 URL https://www.yumpu.com/en/document/view/4764578/thermite-rail-welding-history-process-developments-arema

[18] Shrivatava R 2004 Thermit (Aluminothermic) Welding Method for Rail Joints URL https://www.irfca.org/docs/thermit-welding.html

[19] Gowtam D S, Rao A G, Mohape M, Khatkar V, Deshmukh V P and Shah A K 2008 *International Journal of Self-Propagating High-Temperature Synthesis* **17**(4) 227–232 ISSN 1934-788X URL https://doi.org/10.3103/S1061386208040043

[20] Yeh C L and Wang H J 2009 *Journal of Alloys and Compounds* **485**(1) 280–284 ISSN 0925-8388 URL https://doi.org/10.1016/j.jallcom.2009.06.098

[21] Sereda B, Belokon Y, Belokon K, Kruglyak D, Kruglyak I and Sereda D 2019 Thermodynamics analysis of flowing for SHS-reactions in system Ni-Al alloys *Materials Science and Technology Conference and Exhibition* (Portland) pp 1395–1400 URL https://doi.org/10.7449/2019mst/2019/mst_2019_1395_1400

[22] Sereda B, Belokon Y, Sereda D and Kruglyak I 2019 Modeling of processes for the production of bassed alloys TiAl and NiAl in the conditions of SHS for aerospace applications *Materials Science and Technology Conference and Exhibition* (Portland) pp 137–142 URL https://doi.org/10.7449/2019/MST_2019_137_142

[23] Belokon K and Belokon Y 2018 The Usage of Heat Explosion to Synthesize Intermetallic Compounds and Alloys *Processing, Properties, and Design of Advanced Ceramics and Composites II* (John Wiley & Sons, Ltd) chap 9, pp 109–115 ISBN 9781119423829 URL https://ceramics.onlinelibrary.wiley.com/doi/abs/10.1002/9781119423829.ch9

[24] Skidin I, Vodennikova O, Vodennikov S, Saithareiev L and Telkov S 2021 *E3S Web Conf.* **280** 07015 URL https://doi.org/10.1051/e3sconf/202128007015

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Design and researching of biologically active polymeric hydrogel transdermal materials modified by humic acid

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Abstract. Biologically active polymer hydrogel transdermal materials based on gelatin, sodium alginate, modified by humic acids, were designed and researched. Literature review was carried out and it was proved that humic acids using is perspective for the functional effect on the biologically active polymer hydrogel transdermal properties. It has been found that effective processes for receiving biologically active polymer hydrogel transdermal materials based on gelatin, hydroxypropyl cellulose and sodium alginate can be carried out in different humic acids concentration while achieving an effective increase in hydrogel polymers structuring processes. It can be seen efficiently increasing biologically active polymeric hydrogel transdermal materials based on gelatin and sodium alginate conditional viscosity and the specific electrical conductivity with an increase of humic acids content: from 114 to 135 sec and from 2350 to 2850 mkS/cm, respectively. Humic acids modification in biologically active polymeric hydrogel transdermal materials based on gelatin and sodium alginate caused structure formation with high density, and resistance and with larger agglomerates in hydrogels. It was found that the gelatin-based biopolymer hydrogels modification by humic acids makes it possible to receive biologically active polymeric hydrogel transdermal materials with higher swelling degree. It is shown that the application of new biologically active polymeric hydrogel transdermal materials based on gelatin and sodium alginate modified by humic acids allows improving the skin moisture-lipid balance. From the initial values of 34-36% moisture and 8-10 skin fat, they increase to 58-66% and 52-60%. So, designed polymer hydrogel based on gelatin, sodium alginate, modified by humic acids, are transdermal materials with good properties.

1. Introduction

The modern sustainable development trend in area of biologically active polymers and materials based on them is the technology that allows creating effective systems for drugs and active substances transdermal delivery into the human body [1].

Transdermal delivery systems based on biologically active polymer materials cause increased interest in the drugs introduction through the skin, for local therapeutic action on the affected skin during systemic local drugs delivery. They are also widely used as biologically active materials in the form of various polymer hydrogels [2]. Hydrogels are three-dimensional polymer networks held together by cross-linked covalent bonds and weak cohesive forces in hydrogen or ionic bonds form. This hydrophilic polymeric materials shows an inherent ability to swell in water and some other solvents and is able to absorb and retain more than 10 percents of its weight in water in a gel structure. Hydrogels together with other chemical compounds can form a biologically active composition that can find several local applications on the body and hair surface [3]. Bioadhesive hydrogels using for skin care has important advantages, such as a longer residence time at the application site and a lower product introduction frequency.

Until now, several biologically active hydrogels compositions containing biologically active ingredients have been produced. The selected hydrogels are bioadhesive hydrogel compositions for skin application. Used in biologically active preparations hydrogels can be based on numerous biopolymers, such as collagen, gelatin, hyaluronic acid, alginate, chitosan, xanthan gum, pectin, starch, cellulose and its derivatives.

Based on biopolymers hydrogels are used to design new biologically active agents, such as so-called “beauty masks”. It is claimed that these masks moisturize the skin, restore its elasticity and promote rejuvenation. Superabsorbent hydrogels, particularly acrylate-based materials, are widely used in personal hygiene products to absorb liquids because of their ability to lock moisture away from the skin, promoting skin health, preventing diaper rash and providing comfort.

Today, several types of materials are used to design effective biologically active hydrogels. Both synthetic and bio polymers are widely used. Natural biopolymers fully implement the principle of sustainable development and demonstrate higher biocompatibility and activity compared to synthetic polymers [4].

The transdermal delivery mechanism in such biologically active polymeric hydrogel is that active substances in the hydrogel is delivering to the skin by diffusion. The most effective modern biologically active polymeric hydrogel make of hydroxypropylmethylcellulose [5], hyaluronic acid [6], carboxymethyl cellulose [7], polyvinylpyrrolidone [8] and polylactic glycolic acid [9] and other polymers [10]. For high stability and strength while thermal contact with human skin [11], biologically active polymeric hydrogel actively use their functional modification [12] with various inorganic [13]and organic substances [14]. In our previous works, it was determined that humic substances have a functional effect on the hydrogel biopolymer materials based on gelatin and hydroxypropyl cellulose properties [15]. Especially for increasing structuring processes and strength characteristics [16]. Therefore, it is interesting to study the possibilities of effective modification of biologically active polymer hydrogel materials based on gelatin and sodium alginate with humic substances for receiving systems for active substances delivery systems into the human body.

The *aim* of the article is designing and researching of biologically active polymeric hydrogel transdermal materials modification by humic acid.

2. Materials and methods

The study’s objects for biologically active polymeric transdermal hydrogel designing were:

- food gelatin brand R-11 (Ukraine);
- sodium alginate (China);
- humic acid, were received by extraction from lignite.

The research conditions are the procedure and determination toluene extract output and free humic acids.

First, a gelatin solution (7 % wt.), a defined amount of polymer was placed in 50 mL of distilled water (preheated at 90 ± 2 °C) and stirred to obtain a clear solution. For the co-mixture of gelatin and sodium alginate, a defined amount of sodium alginate (2.5 % wt.) was added in the previously prepared gelatin (7 % wt.) solution and allowed to mix homogeneously on a magnetic stirrer (Jisico Co. Ltd., South Korea). After that, by mixing, solutions with humic acids were obtained, in which the concentration of the latter was 2.5, 5 and 7.5 % wt.

Conductometric studies of biologically active polymeric hydrogel solutions were carried out on a combined TDS-meter HM digital COM-100 (USA), scale range: specific conductivity: from 0 to 9990 mkS/cm; temperatures: from 0 to 55 °C; Error: ± 2%.

Microscopic studies of biologically active polymeric hydrogel were carried out using the electron microscope Digital Microscope HDcolor CMOS Sensor (China).

The viscosity of biologically active polymeric hydrogel was determined according to ISO 2431. The method is based on determining the viscosity of a solution of biologically active polymeric hydrogel solution with free flow is taken as the time of continuous flow in seconds test material (50 cm^3) through a calibrated nozzle with 4 mm diameter of a viscometer (VZ-246) at a certain temperature.

The swelling degree of biologically active polymeric hydrogel transdermal materials was calculated according to formula (2) [15]:

$$Q = 100 \cdot \frac{m_1 - m}{m}, \tag{1}$$

where m_1 is the mass of the swollen sample, g.; m is the mass of the sample before standing in an aqueous solution, g.

To determine the moisture-lipid skin balance a professional skin moisture and oiliness analyser SK-92 (China) was used. This device operates on the basis of the Bioelectric Impedance Analysis (BIA) method – measuring the skin resistance tissues under the electric current. The moisture-lipid balance was measured in the area around the eyes before and after applying biologically active polymeric hydrogel transdermal materials for 15 minutes in five 23-year-old women (figure 1).

The skin moisture and oiliness range is from 0 to 99.9%, accuracy: 0.1%.

3. Results

The biologically active polymeric hydrogel transdermal materials based on gelatin and sodium alginate conditional viscosity and conductivity dependence from on the different humic acid content is shown in figure 2.

Next studies were carried out to determine the humic acids modification effect on the most important operational properties of biologically active polymeric hydrogel transdermal materials based on gelatin and sodium alginate: swelling degree and effect on the skin moisture-lipid balance. Table 1 shows the operational properties of biologically active polymeric hydrogel transdermal materials based on gelatin and sodium alginate modified by humic acids.

Table 1. Operational properties of biologically active polymeric hydrogel transdermal materials based on gelatin and sodium alginate modified by humic acids.

Humic acid content (%wt.)	Swelling degree (%wt.)	Moisture/lipid, %
Pure gelatin-sodium alginate composition	19.82	58-60/52-54
2.5	27.17	60-62/55-56
5	26.83	62-64/56-58
7.5	23.21	64-66/58-60

Figure 1. Model (women) with biologically active polymeric hydrogel transdermal materials in the area around the eyes.

4. Discussion

In hydrogel materials for transdermal delivery it is very important to ensure prolonged bioavailability of target biologically active substances through the skin barrier while high adhesion to the skin, stability of their geometric dimensions and shape preservation in temperature conditions throughout the entire period of exposure to human skin. Such properties of hydrogel materials for transdermal delivery can be achieved by researching hydrogels viscosity, electrical conductivity and structural formation optimized level. For example, in [17] it was shown that by increasing the viscosity and structuring of polyacrylamide-polydopamine hydrogels with mesoporous silica nanoparticles, hydrogel patches with high adhesiveness for transdermal drug delivery were obtained. Therefore, the initial studies consisted in determining the conditional viscosity and electrical conductivity dependence of bioactive humic-polymer hydrogel transdermal materials based on gelatin and sodium alginate, as well as based on hydroxypropyl methylcellulose and sodium alginate, on the different humic acids content in them. According to [18], the electrical conductivity of bioactive humic polymer hydrogel transdermal materials, which is related to the content of ionogenic substances, can actually be used as hydration level measure using a high-density and rigid network in water-soluble polymer hydrogel materials. Therefore, it is important to study non-cytotoxic alginate–gelatin hydrogels modified with humic acids as biomaterials with good mechanical strength and biocompatibility, which are advisable to use in transdermal patches, microcapsules for bioactive compounds, cells and preparations, as well as in regenerative medicine (for example, for bone tissue regeneration) or as a soft tissue patch for wound healing. From the data in the figure 2 it can be seen increasing biologically active polymeric hydrogel transdermal materials based on gelatin and sodium alginate conditional viscosity and the specific electrical conductivity with humic acids content increase: from 114 to 135 sec and from 2350 to 2850 mkS/cm, respectively. Such changes

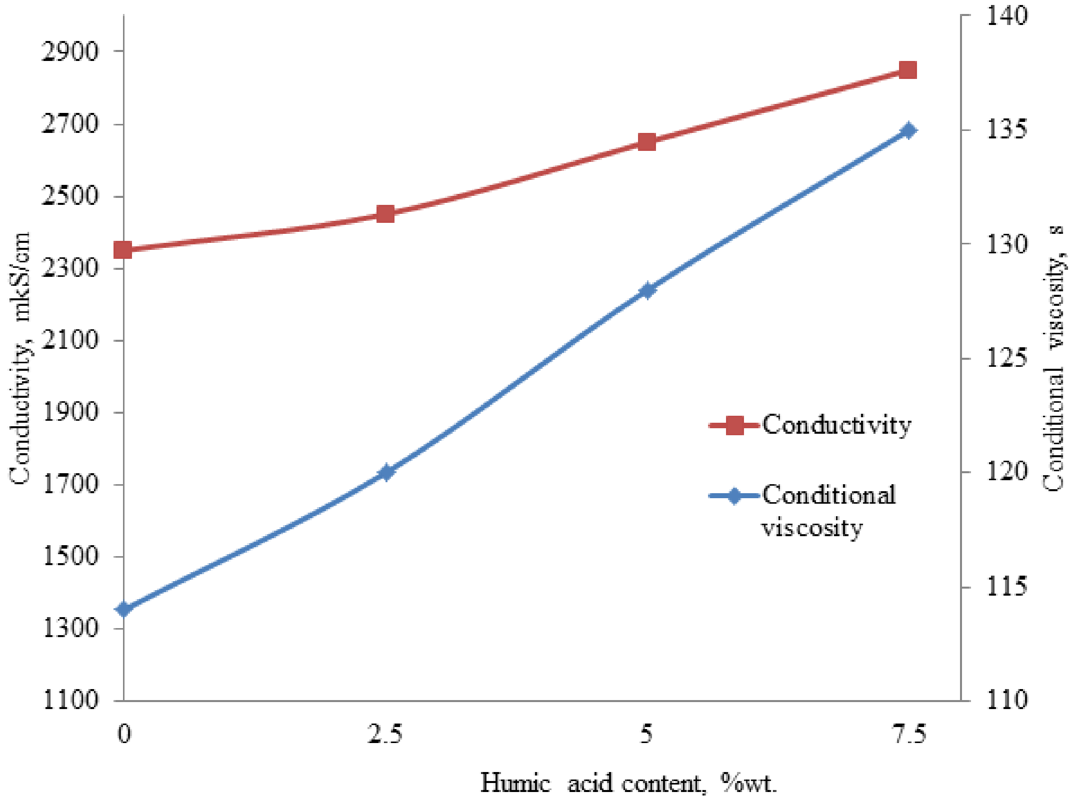

Figure 2. The conditional viscosity and conductivity dependencies of biologically active polymeric hydrogel transdermal materials based on gelatin and sodium alginate with different humic acid content.

indicate the following features humic acids modification of the structure formation processes in biologically active polymeric hydrogel transdermal materials based on gelatin and sodium alginate: more density [19] and rigid network of biologically active polymeric hydrogel [20]. Also the larger number agglomerates formation [21] in biologically active polymeric hydrogel [22] (figure 3).

Table 1 shows that the modification of gelatin-based biopolymer hydrogels by humic acids makes it possible to obtain biologically active polymeric hydrogel transdermal materials with an increased swelling degree. The larger number agglomerates formation in biologically active polymeric hydrogel transdermal materials based on gelatin and sodium alginate on the different humic acid content is clearly visible from the microscopic studies results. It should be noted that the hydrogel delamination in biologically active polymeric hydrogel transdermal materials based on gelatin and sodium alginate on the different humic acid content into the aqueous phase and the structured polymer phase does not occur. Increasing the degree of swelling when modified with humic acids due to more rigid network hydrogels formation makes it possible to achieve long-term prolonged transdermal release of drugs, stability of their geometric dimensions and shape in temperature conditions throughout the entire period of exposure to human skin, and easier separation from the skin after application. So, it is important to note that the using new biologically active polymeric hydrogel transdermal materials based on gelatin and sodium alginate modified by humic acids allows to improve the skin moisture-lipid balance. So, from the initial values of 34-36% moisture and 8-10 skin fat, they increase to 58-66% and 52-60%. As it can be seen in table 1, the improvement in skin moisture-lipid balance became more with an increase in humic substances content. Actually, modification with humic acids makes it possible

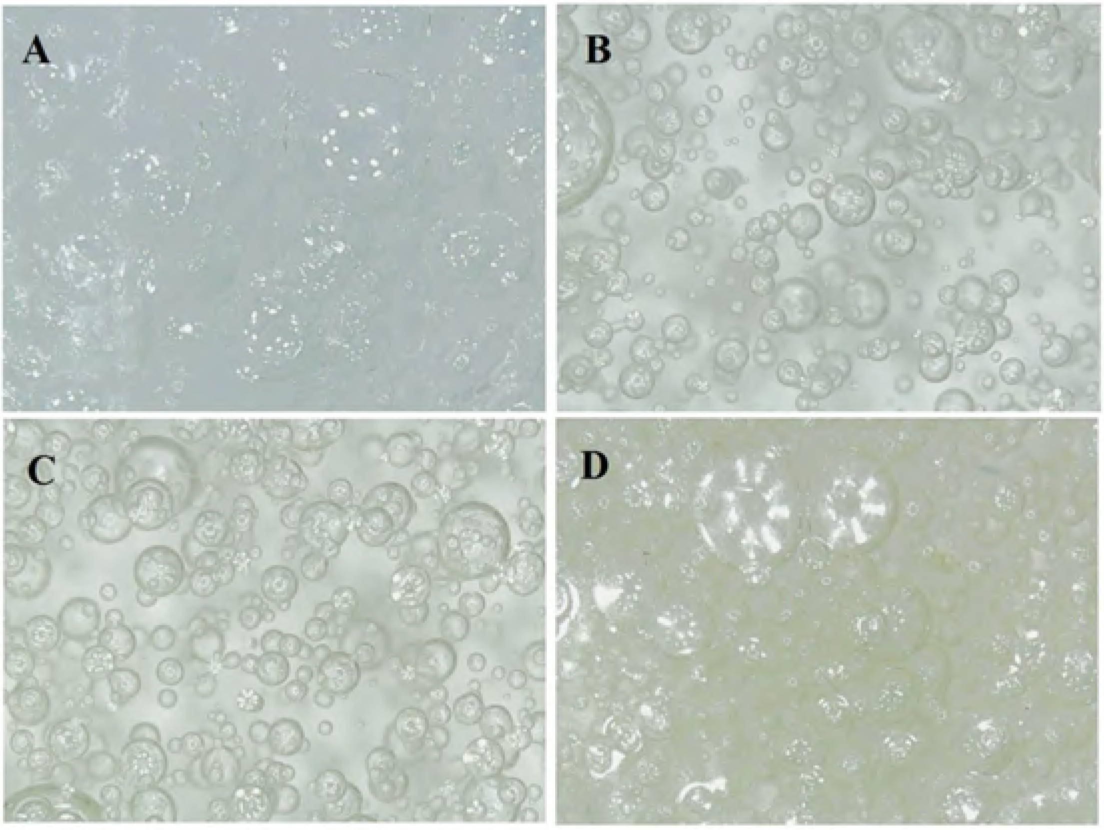

Figure 3. Microscopic studies of of biologically active polymeric hydrogel transdermal materials based on gelatin and sodium alginate on the different content of humic acid: A – pure gelatin and sodium alginate hydrogel; B – gelatin and sodium alginate hydrogel + 2.5 % wt. of humic acid; C – gelatin and sodium alginate hydrogel + 5 % wt. of humic acid; D – gelatin and sodium alginate hydrogel +7. % wt. of humic acid.

to obtain hydrogel transdermal materials, which, when applied to the human body, will allow to regulate skin moisture-lipid balance uniformly and for a long time.

In fact, thanks to the biologically active polymeric hydrogel transdermal materials based on gelatin and sodium alginate modified by humic acids using, it becomes possible to transfer the skin from slightly moist-fatty hard to highly moist-fatty elastic condition. The moisture-lipid balance skin improving increases with increasing the humic substances content.

5. Conclusions

The effective biologically active polymeric hydrogel transdermal materials based on gelatin and sodium alginate, modified by different humic acid content, were received and researched. By carrying out rheological, conductometric and microscopic studies, it was found that the modification of gelatin-sodium alginate systems by humic acids allows receive polymer hydrogels with high structuring degree. Modification of gelatin-based biopolymer hydrogels by humic acids makes it possible to obtain biologically active polymeric hydrogel transdermal materials with an increased swelling degree and ability to improve the skin moisture-lipid balance: from the initial moisture 34-36% and fatness 8-10%, they increase to 58-66% and 52-60%. In future researching is perspective to determine transdermal level of designed biologically active polymer hydrogels for most important medicine and cosmetic biologically active substances.

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References

[1] Kim S, Oh T, Lee H and Nam J M 2022 *Materials Chemistry Frontiers* **6**(16) 2152–2174 URL https://doi.org/10.1039/D2QM00039C
[2] Jaipan P, Nguyen A and Narayan R J 2017 *MMRS Communications* **7**(3) 416–426 URL https://doi.org/10.1557/mrc.2017.92
[3] Sionkowska A 2011 *Progress in Polymer Science* **36**(9) 1254–1276 URL https://doi.org/10.1016/j.progpolymsci.2011.05.003
[4] Migdadi E M, Courtenay A J, Tekko I A, McCrudden M T, Kearney M C, McAlister E, McCarthy H O and Donnelly R F 2018 *Journal of Controlled Release* **285** 142–151 URL https://doi.org/10.1016/j.jconrel.2018.07.009
[5] Kim J Y, Han M R, Kim Y H, Shin S W, Nam S Y and Park J H 2016 *European Journal of Pharmaceutics and Biopharmaceutics* **105** 148–155 URL https://doi.org/10.1016/j.ejpb.2016.06.006
[6] Du H, Liu P, Zhu J, Lan J, Li Y, Zhang L, Zhu J and Tao J 2019 *European Journal of Pharmaceutics and Biopharmaceutics* **11** 43588–43598 URL https://doi.org/10.1021/acsami.9b15668
[7] Mistilis M J, Bommarius A S and Prausnitz M R 2015 *Journal of Pharmaceutical Sciences* **104**(2) 740–749 URL https://doi.org/10.1002/jps.24283
[8] Tang J, Wang J, Huang K, Ye Y, Su T, Qiao L, Hensley M T, Caranasos T G, Zhang J, Gu Z and Cheng K 2018 *Science Advances* **4**(11) 9365 URL https://doi.org/10.1126%2Fsciadv.aat9365
[9] Nataraj D, Sakkara S, Meghwal M and Reddy N 2018 *International journal of biological macromolecules* **120**(Pt A) 1256–1264 URL https://doi.org/10.1016/j.ijbiomac.2018.08.187
[10] He R, Niu Y, Li Z, Li A, Yang H, Xu F and Li F 2020 *Advanced Healthcare Materials* **9** 1901201 URL https://doi.org/10.1002/adhm.201901201
[11] Martnez-Martnez M, Rodrguez-Berna G, Bermejo M, Gonzalez-Alvarez I, Gonzalez-Alvarez M and Merino V 2019 *European Journal of Pharmaceutics and Biopharmaceutics* **136** 174–183 URL https://doi.org/10.1016/j.ejpb.2019.01.009
[12] Li Y, Zhang H, Yang R, Laffitte Y, Schmill U, Hu W, Kaddoura M, Blondeel E J M and Cui B 2019 *Microsystems and Nanoengineering* **9**(41) 9365 URL https://doi.org/10.1038/s41378-019-0077-y
[13] Vakili M, Deng S, Li T, Wang W, Wang W and Yu G 2018 *Chemical Engineering Journal* **347** 1256–1264 URL https://doi.org/10.1016/j.cej.2018.04.181
[14] Garnica-Palafox I and Sanchez-Arevalo F 2016 *Chemical Engineering Journal* **151** 1073–1081 URL https://doi.org/10.1016/j.carbpol.2016.06.036
[15] Lebedev V, Miroshnichenko D, Zhang X, Pyshyev S and Savchenkoand D 2021 *Petroleum and Coal* **63**(3) 646–654 URL https://www.vurup.sk/wp-content/uploads/2021/08/PC-X_Miroshnichenko_31_rev1.pdf
[16] Lebedev V, , Sizhuo D, Zhang X, Miroshnichenko D, Pyshyev S and Savchenko D 2022 *Petroleum and Coal* **64**(3) 539–546 URL https://www.vurup.sk/wp-content/uploads/2022/09/PC-X_Miroshnichenko-178.pdf
[17] Jung H, Kim M K, Lee J Y, Choi S W and Kim J 2020 *Advanced Functional Materials* **30**(42) 2070280 URL https://doi.org/10.1002/adfm.202070280
[18] Kaklamani G, Kazaryan D, Bowen J, Iacovella F, Anastasiadis S H and Deligeorgis G 2018 *Regenerative Biomaterials* **5** 293–301 URL https://doi.org/10.1093/rb/rby019
[19] Rizwan M, Gilani S R, Durani A I and Naseem S 2021 *Journal of advanced research* **33** 15–40 URL https://doi.org/10.1016/j.jare.2021.03.007
[20] Cacopardo L, Guazzelli N, Nossa R, Mattei G and Ahluwalia A 2019 *Journal of the mechanical behavior of biomedical materials* **89** 162–167 URL https://doi.org/10.1016/j.jmbbm.2018.09.031
[21] Kaklamani G, Kazaryan D, Bowen J, Iacovella F, Anastasiadis S H and Deligeorgi G 2019 *Regenerative biomaterials* **5**(5) 293–301 URL https://doi.org/10.1093/rb/rby019
[22] Konsta A, Daoukaki Dand Pissis P and Vartzeli K 1999 *Solid State Ionics* **125** 293–301 URL https://doi.org/10.1016/S0167-2738(99)00180-0

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Ceramic-inorganic polymer composites for protection against electromagnetic radiation mechanical properties designing

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Ceramic-inorganic polymer composites for protection against electromagnetic radiation mechanical properties designing

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Abstract. The possibility of designing mechanical properties of ceramic-inorganic polymer composites for protection against electromagnetic radiation is considered. As a result, the mechanical properties of polymer composite based on polyamide, modified with ceramic-inorganic graphite-ferromagnetic fillers (silicon carbide, chromium oxide Cr_2O_3 and graphite) was received and optimized. The strength characteristics complex of ceramic-inorganic polymer composites with silicon carbide SiC, chromium oxide Cr_2O_3 and graphite content in diapason 5-15 % wt. were studied. It was established that the optimal strength characteristics can be received using binary modification of polyamide with ceramic-inorganic graphite-ferromagnetic fillers: polyamide 6 – SiC 10% wt. – Cr_2O_3 10% wt. and polyamide 6 – SiC 10% wt. – graphite 10% wt. Using mathematical modeling, it was established that the polyamide 6 – SiC 10% wt system is the most optimal for three-component complex modification with ceramic-inorganic graphite-ferromagnetic fillers – Cr_2O_3 10% wt. – graphite 10% wt. By design experimental-statistical mathematical models in equal regressions, mathematical optimization of mechanical properties of polymeric ceramic-inorganic composites contains for protection against electromagnetic radiation was carried out. Designed polymer ceramic-inorganic composites for protection against electromagnetic radiation according to their strength characteristics can be used for modern radio absorbing materials production.

1. Introduction

Nowadays, the production of various radio-electronic equipment is actively expanding. The main direction is radio-electronic equipment improving properties: reducing the size and energy losses, better accuracy and speed, etc. Many technologies are already transit to a higher frequency range. So there is a need for materials with appropriate electromagnetic characteristics, which are necessary for matching and protecting various electromagnetic ranges components.

As now there is no single-component material that could achieve a high absorption capacity in a wide frequency band. Such composite materials are used for: biological objects protection, the electromagnetic devices compatibility [1], electromagnetic waves reflection reducing [2].

Composite materials of various nature are actively used to ensure protection against electromagnetic radiation. It is also correspond the sustainable development conception. The main feature of composite materials is that they represent a combination of two or more constituent components and have new properties different from the components separately properties. Composites are easy to production and provide new, unattainable for traditional materials, physico-chemical properties, such as flexibility, high strength, elasticity, as well as unique new characteristics [3].

Typical materials for absorbing electromagnetic radiation are:

1) conductive powdered materials (coal, carbon black, graphite, metals – steel, cast iron, iron, aluminum, cobalt, lead, zinc, tin, copper, etc. [4], metal salts) with spherical, cylindrical, flaky, etc. shape of particles [5];
2) conductive carbon, metal and metal-carbon fibers, carbon fabrics, metal threads, plates, foil strips, wire scraps, meshes of a complex shape, gratings, resonant elements in the form of cross-shaped dipoles [6] or closed conductors (rings) etc. [7];
3) metallized carbon and polymer fibers, fabrics, films, macrospheres;
4) magnetic fillers – ferrites of different chemical composition (mostly magnetically soft), as well as magnetic powders of metals and amorphous Fe alloys, Fe-Co-Ni alloys; perm, etc.) [8];
5) dispersed semiconductors: charred organic silicon fabrics and fibers [9],
6) dielectrics, in particular, easily polarized organic substances (retinyl Schiff salts) [10], biopolymers (chitin), etc.

In modern scientific literature, many compositions of ferrite components for absorbers of various ranges are described [11]. These materials are intended for the electromagnetic radiation range of 0.5-12 GHz. The size of particles of ferrite powders that effectively absorb electromagnetic radiation at frequencies of 0.5-1.5 GHz is 1.65-0.7 mm, and in the range of 2.5-12 GHz – 0.1 mm. The advantage of ferrite absorbers is their small thickness (several millimeters). However, they are time-consuming to manufacture and non-technological, as it is necessary to stick ferrite plates on the surface of the metal part being protected. In addition, such absorbers have an insufficiently wide band of operating frequencies [5].

By varying fillers concentration it is possible to achieve the required electromagnetic properties: high absorption coefficient, complex dielectric and magnetic permeability, and shielding level. In modern scientific sources, there is a lot of research on receiving materials for protection against electromagnetic radiation. Most research concerns the design effective materials for protection against electromagnetic radiation based on mixtures and composites of fillers with magnetic properties (such as ferrites [3], metals [6]) and various dielectrics – ceramic, polymer and other matrices [7]. As an active phase (filler) of composites, carbon-containing materials (carbon nanotubes [7], graphite [12], carbonyl iron, fullerenes, etc.) [8], ferrite powders [9] are used widly. The composite materials research based on ferroelectrics [10] and multiferroics is actively developing [11].The material absorbing high-frequency electromagnetic radiation based on barium hexaferrite substituted with diamagnetic ions are demonstrated [13]. It is shown that absorbing high-frequency electromagnetic radiation in such barium hexaferrite substituted to higher frequencies due to an increase in the magnetocrystal anisotropy [14].

Thermoreactive polymer composites containing silicon carbide [12], carbon fibers [15], carbon black [16] and carbon nanotubes [17] are also effective. They provide protection as radio shielding materials and coatings due to the absorption mechanisms combination [18]: natural ferromagnetic resonance, resonance of domain boundaries movement, eddy current losses and repolarization, multiple imprints and etc.

Such materials effectively provide protection against electromagnetic radiation, but their disadvantages include the complexity synthesis and high cost.

Therefore, polymer composites for protection against electromagnetic radiation based on various thermoplastic matrices (polyvinylbutyral [19], polypropylene [20], polyvinylidene chloride [21], etc.) have been recently designed. In such polymer composites, inorganic ferromagnetic fillers are used. They have better technological, operational and economic characteristics.

In our previous work [22], polymer composites for protection against the electromagnetic radiation absorption based on thermoplastic polyamide 6 and silicon carbide were received. This polymer composites are transparent in the millimeter frequency range (approximately 3 dB, this is a 2-fold attenuation), have a small absorption coefficient but low mechanical properties.

Overall efficiency electromagnetic radiation absorption for received compositions was insufficient. So further research in the framework of complex ceramic-inorganic graphite-ferromagnetic fillers application was carried out as expedient.

The *aim* of the article is ceramic-inorganic polymer composites mechanical properties designing for protection against electromagnetic radiation.

2. Materials and methods

For polymeric ceramic-inorganic composites research, that can be used for electro-magnetic protection coating production:

- polyamide 6 brand Durethane (Bayer, Germany);
- silicon carbide SiC powder – size 50-65 microns;
- chromium oxide Cr_2O_3 powder – size 2-5 microns;
- graphite powder – size 20-25 microns, which was received from graphite samples (were used standard graphite blanks).

After analysis, the graphite sample was additionally crushed to 100% to the class content less than 0.075 mm using a cylindrical mill on elastic hangers and scattered on a mechanical disperser on 0.02 mm grids.

Quality indicators of carbon graphite sample and scattering results (2 samples) are given in table 1 and table 2.

Polymer composites were production by extruding.

Strength characteristics determination was carried out according to ISO 180 and ISO 178. Complex strength characteristics determination of polymeric ceramic-inorganic composites for electromagnetic radiation absorption was carried out on pendulum copra at a temperature of 20 °C. For each composition, 20 parallel measurements were made.

Table 1. Quality indicators of carbon graphite sample.

Characteristics	Symbol, unit of measurement	Value %
Total moisture	W_t^r,%	0.10
Analytical moisture	W^a,%	0.10
Ashiness	A^d,%	0.18
Carbon content	C^d,%	99.06
Hydrogen content	H^d,%	0.76

Table 2. Results graphite grid analyses.

Class, mm	Value, %
less of 0.02	31.4-43.2
0.02-0.075	56.8-68.6

Optimization experimental-statistical mathematical models construction in equal regressions form was carried out using the STATISTICA software.

3. Results and discussion

Primary studies were directed at studying the SiC, Cr_2O_3 and graphite impact on strength properties complex of polyamide 6 compositions. From previous work [22], it was found that increasing the content of SiC in polyamide 6 led to an increase in both IR and BSDB.

Optimal content of fillers for those was found at level 5%wt. But overall efficiency of received compositions protection against electromagnetic radiation was insufficient, this article researched compositions with a higher content of SiC – 10% wt., and optimized the content of Cr_2O_3 and graphite in the range of 5-15 % wt. Also, to establish the synergistic effect the three different ceramic-inorganic graphite-ferromagnetic fillers integrated effect, polyamide 6 – SiC – Cr_2O_3 – graphite systems were studied. In the table 3 shown the filler's level impact of polymer ceramic-inorganic composites based on the polyamide 6 – SiC – Cr_2O_3 – graphite system on the IR and BSDB. From the data in table 3, it can be seen that the introduction of polyamide 6 – SiC 10% wt. into the system of chromium oxide Cr_2O_3 and graphite increases their IR and BSDB.

Table 3. Filler's level impact of polymer ceramic-inorganic composites based on the polyamide 6 – SiC – Cr_2O_3 – graphite system on the IR and BSDB.

Composites	IR, MPa	BSDB, MPa
Polyamide 6 – 10 % wt. SiC	38	175
Polyamide 6 – 10 % wt. SiC:		
5 % wt. graphite	43	183
10 % wt. graphite	52	190
15 % wt. graphite	50	185
Polyamide 6 – 10 % wt. SiC:		
5 % wt. Cr_2O_3	40	180
10 % wt. Cr_2O_3	45	185
15 % wt. Cr_2O_3	44	182
Polyamide 6 – 10 % wt. SiC:		
5 % wt. Cr_2O_3 – 5 % wt. graphite	42	185
10 % wt. Cr_2O_3 – 10 % wt. graphite	47	188

The maximum level of the studied strength characteristics is typical for the systems of polyamide 6 – SiC 10% wt. – graphite 10% wt. Also high level of strength is also observed in the triple complex system of ceramic-inorganic fillers polyamide 6 – SiC 10% wt. – Cr_2O_3 10% wt. – graphite 10 % wt. It can be concluded that binary modification with ceramic-inorganic graphite-ferromagnetic fillers of composites based on the systems polyamide 6 – SiC 10% wt. – Cr_2O_3 10% wt. and polyamide 6 – SiC 10% wt. – graphite 10% wt. is optimal for increasing its strength characteristics. For three-component complex modification with ceramic-inorganic graphite-ferromagnetic fillers, the polyamide 6– SiC 10% wt. – Cr_2O_3 10 % wt. – graphite 10 % wt. system is the most optimal. Also, while studying the spectral characteristics of the polymeric ceramic-inorganic composites, it was established that the highest level of reflection coefficient over 23 % is typical for polyamide 6 systems of 6-10% wt. silicon carbide – 10% wt. chromium oxide Cr_2O_3 – 10% wt. graphite, which is related to the complex nature of the action of various ceramic-inorganic graphite-ferromagnetic fillers. This system is almost 2.5 times superior to previously obtained composites [20] in level of spectral characteristics.

For building a mathematical model to optimize mechanical properties of ceramic-inorganic polymer composites for protection against electromagnetic radiation, an analysis datas given in the table 3 was carried out. Ninth experiments were made, the composition of the composite varied within the following limits: polyamide 6 + SiC 10 % wt. – from 83.32 to 100 % wt.; graphite – from 0 to 13.04 % wt.; Cr_2O_3 – from 0 to 13.04 % wt. At the same time, the IS values ranged from 38 to 52.5 MPa, and the BSDB values ranged from 175 to 190 MPa. Table 4 shows the pairwise correlation coefficients between indicators.It can be concluded that the indicators of IS and BSDB are interrelated, which is confirmed by the high value of the pairwise correlation coefficient between them (0.860).

Table 4. Pairwise correlation coefficients of mathematical model for composition mechanical properties optimization.

	IR	BSDB	Polyamide 6-SiC 10%wt.	Graphite	Cr_2O_3
IR	1.000				
BSDB	0.860	1.000			
Polyamide 6-SiC 10%wt.	-0.655	-0.716	1.000		
Graphite	0.788	0.663	-0.524	1.000	
Cr_2O_3	-0.102	0.088	-0.524	-0.451	1.000

Polyamide 6 + SiC 10 % wt. content increasing leads IR and BSDB decreasing. The same time, graphite content increasing leads IS and BSDB increasing. The Cr_2O_3 content impact on mechanical properties is insignificant.

Table 5 shows the calculated mathematical equations that describe content of polyamide 6 + 10%wt. SiC, graphite and Cr_2O_3 impact on the IR and BSDB, as well as statistical indicators.

Table 5. Mathematical equations and statistical indicators of mathematical model for composition IR and BSDB optimization.

Mathematical model	R	R^2
IR=69.682-0.303(polyamide 6+ SiC 10%)+0.584graphite+0.02Cr_2O_3	0.838	0.702
BSDB=69.682-0.440(polyamide 6+SiC10%wt.)+0.359graphite+0.01Cr_2O_3	0.792	0.627

Multiple correlation indicators R and R^2 of the developed models are high enough ($R = 0.792 - 0.838; R^2 = 0.627 - 0.702$), and level of standard error 2.921-3.115 MPa allow to use built equations for the IR and BSDB prediction of designed ceramic-inorganic polymer composites for protection against electromagnetic radiation.

4. Conclusions

The article considers the possibility to receive polymeric ceramic-inorganic composites for protection against electromagnetic radiation. As a result the polymer polyamide composites modified with ceramic-inorganic graphite-ferromagnetic fillers: SiC, Cr_2O_3 and graphite were received.

The strength complex characteristics of compositions with carbide SiC – 10%wt . were studied. For them content of Cr_2O_3 and graphite in range 5-15%wt. was optimized. It was found that the optimal strength characteristics shows composites based on the systems polyamide 6 – SiC 10%wt. – $Cr_2O_3$10%wt. and polyamide 6 – SiC 10%wt. – graphite 10%wt. when it is binary modification with ceramic-inorganic graphite-ferromagnetic fillers. For three-component complex modification with ceramic-inorganic graphite-ferromagnetic fillers, the most optimal system is polyamide 6 – SiC 10%wt. – $Cr_2O_3$10%wt. – graphite 10%wt with highest mechanical and spectral properties. By design experimental-statistical mathematical models in equal regressions, mathematical optimization of polymeric ceramic-inorganic composites mechanical properties for protection against electromagnetic radiation was carried out. Received polymeric ceramic-inorganic composites for absorbing electromagnetic radiation can be used for radio-absorbing materials production according to their strength and spectral characteristics.

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References
[1] Lv H, Zhang H, Ji G and Xu Z J 2016 *ACS applied materials & interfaces* **6**(10) 6529–6538 URL https://doi.org/10.1021/acsami.5b12662
[2] Wang H, Xiang L, Wei W, An J, He J, Gong C and Hou Y 2017 *ACS applied materials & interfaces* **9**(48) 42102–42110 URL https://doi.org/10.1021/acsami.7b13796
[3] Wang F, Wang X, Zhu J, Yang H, Kong X and Liu X 2016 *Scientific Reports* **6** 37892 URL https://doi.org/10.1038/srep37892
[4] Lv R, Kang F, Gu J, Gui X, Wei J, Wang K and Wu D 2008 *Applied Physics Letters* **93** 223105 URL https://doi.org/10.1063/1.3042099
[5] Liu Q, Xu X, Xia W, Che R, Chen C, Cao Q and He J 2015 *Nanoscale* **7** 1736–1743 URL https://doi.org/10.1039/c4nr05547k
[6] Lv H, Ji G, Wang M, Shang C, Zhang H and Du Y 2016 *Journal of Alloys and Compounds* **615** 1037–1042 URL https://doi.org/10.1016/j.jallcom.2014.07.118
[7] Du H, Liu P, Zhu J, Lan J, Li Y, Zhang L, Zhu J and Tao J 2018 *Carbon* **127** 643–652 URL https://doi.org/10.1021/acsami.9b15668
[8] Lebedev V, Miroshnichenko D, Zhang X, Pyshyev S, Savchenkoand D and Nikolaichuk Y 2021 *Petroleum and Coal* **63**(4) 953–962 URL https://www.vurup.sk/wp-content/uploads/2021/12/PC-X_Miroshnichenko_75.pdf
[9] Kruglyak Y O and Strikha M V 2019 *Sensor Electronics and Microsystem Technologies* **16**(1) 24–49 URL http://doi.org/10.18524/1815-7459.2019.1.159485
[10] Kruglyak Y O and Strikha M V 2019 *Sensor Electronics and Microsystem Technologies* **16**(2) 5–31 URL https://doi.org/10.18524/1815-7459.2019.2.171224
[11] Salahuddin S, Ni K and Datta S 2018 *Nature electronics* **1** 442–450 URL https://doi.org/10.1038/s41928-018-0117-x
[12] Morozzi A, Hoffmann M, Mulargia R, Slesazeck S and Robutti E 2022 *Journal of Instrumentation* **17** C01048 URL https://doi.org/10.1088/1748-0221/17/01/C01048
[13] Trukhanov S V, Trukhanov A V, Kostishin V G, Panina L V, Kazakevich I S, Turchenko V A, Oleinik V V, Yakovenko E S and Matsui L Y 2016 *Journal of Experimental and Theoretical Physics* **123** 461–469 URL https://doi.org/10.1134/S1063776116090089
[14] Trukhanov A V, Kostishin V G, Korovushkin V V, Panina L V, Trukhanov S V, Turchenko V A, Polyakov I S, Rakhmatullin R K, Filatov G A, Zubar' T I, Oleinik V V, Yakovenko E S, Matsui L Y, Vovchenko L L, Launets V L and Trukhanova E L 2018 *Chemical Engineering Journal* **60** 1768–1777 URL https://doi.org/10.1134/S1063783418090342
[15] Shah A, Wang Y, Huang H, Zhang L, Wang D, Zhou L, Duan Y, Dong X and Zhang Z 2015 *Composite Structures* **131** 1132–41 URL https://doi.org/10.1016/j.compstruct.2015.05.054
[16] Al-Ghamdi A A, Al-Hartomy O A, Al-Solamy F R, Dishovsky N, Malinova P, Atanasova G and Atanasov N 2016 *Composites Part B: Engineering* **96** 231–41 URL https://doi.org/10.1016/j.compositesb.2016.04.039

[17] Hu J, Zhao T, Peng X, Yang W, Ji X and Li T 2018 *Composites Part B: Engineering* **134** 91–7 URL https://doi:10.1016/j.compositesb.2017.09.071

[18] Makarova T, Geydt P, Lahderanta I Z E, Komlev A, Zyrianova A, Kanygin M, Sedelnikova O, Suslyaev V, Bulusheva L and Okotrub A 2016 *Composites Part B: Engineering* **91**(42) 505–12 URL https://doi.org/10.1016/j.compositesb.2016.01.040

[19] Zhu G, Cui X, Zhang Y, Chen S, Dong M, Liu H, Shao Q, Ding T, Wu S and Guo Z 2019 *Polymer* **172** 415–422 URL https://doi.org/10.1016/j.polymer.2019.03.056

[20] Lai H, Li W, Xu L, Wang X, Jiao H, Fan Z, Lei Z and Yuan Y 2020 *Chemical Engineering Journal* **400** 125322 URL https://doi.org/10.1016/j.cej.2020.125322

[21] Liang C, Hamidinejad M, Ma L, Wang Z and Park C B 2020 *Carbon* **156** 58–66 URL https://doi.org/10.1016/j.carbon.2019.09.044

[22] Lebedev V, Kryvobok R, Cherkashina A, Bliznyuk A, Lisachuk G and Tykhomyrova T 2022 Design And Research Polymer Composites For Absorption Of Electromagnetic Radiation *2022 IEEE 3rd KhPI Week on Advanced Technology (KhPIWeek)* pp 1–4 URL https://doi.org/10.1109/KhPIWeek57572.2022.9916467

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Enhancing the quality of the initial discovery of carbonate gas deposits in the Zahoryanska field zone by improving the drilling mud

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Enhancing the quality of the initial discovery of carbonate gas deposits in the Zahoryanska field zone by improving the drilling mud

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Abstract. The results of studies of the flushing fluids influence on the capacity-filtration characteristics of carbonate rocks are presented. It was found that hydrogel-magnesium fluids using desulfurized bischofite are the optimal flushing fluid for opening carbonate-type formations. Solutions of the hydrogel-magnesium type, with a relatively small depth of penetration into the formation, are distinguished, among others, by a high coefficient of recovery of permeability. After the application of such solutions and subsequent acid treatment, the pore space of the formation can be almost completely restored. The effect of the presence of sulfate ions in the bischophyte on the permeability and recovery coefficient of the carbonate core was investigated. It was established that in the presence of sulfate ions in bischophyte, the permeability and formation recovery in the presence of formation water decreases by 11.53 times, and when using pure bischophyte – only by 1.29 times. An improved method of preparing bischofite for use in washing liquids has been developed. The results of industrial use of the developed method are given.

1. Introduction

Ukraine has significant deposits of developed mineral deposits. Nowadays, 90 types of minerals have been explored, which are concentrated in almost 8,000 deposits. For sustainable development, it is necessary to increase the efficiency of the natural resources using [1–3].

Provision of own energy resources is a guarantee of not only energy, but also state independence of Ukraine. Unfortunately, in recent years, gas production in Ukraine has begun to steadily decrease. In 2020, 20.23 billion cubic meters of gas were produced, which is 2.2% less than in 2021 (19.79 billion cubic meters), in 2022 Ukraine is going to produce 18.5 billion cubic meters. m of gas, which is 6.6% (1.3 billion cubic meters) less than in 2021. The bloody war between Russia and Ukraine in 2022 radically changed the national gas sector: there was a significant decrease in both consumption and production due to Russian bombing of our gas fields.

Also, the reasons that prevent the realization of the domestic hydrocarbon potential are the depletion of deposits (by 65 – 70%), which causes a sharp drop in production and difficult access (the average depth of the deposits exceeds 3500 m) and the dispersion of a large number of small fields – reserves 89% of deposits do not exceed 5 billion m^3. At the same time, in order to ensure the sustainable development of the oil and gas sector, the annual growth of the raw material base should be 2 – 3 times higher than the production level [4].

The drilling of oil and gas wells leads to a destruction of the natural balance of fluid saturation of productive layers. As a result of the penetration of leachate and the solid phase of washing or process fluids, the character of the saturation of the pore space of the rocks in the bottomhole formation zone of the formation changes, processes occur that are caused by the physical and chemical interaction of drilling muds with the rock and formation fluids, which significantly worsen the filtration properties of the rocks [5].

The influence of flushing fluids on productive formations is due to penetration into the pore space of the filtrate collector and dispersed phase, swelling of clay cement, formation of solid sediments and emulsions during interaction with formation fluids, reduction of effective pore volume [5, 6]. All this leads to deterioration of productive characteristics of wells. Therefore, the question arises of preserving the natural productive properties of formations during the construction, repair and restoration of wells. An equally important task is the choice of means and methods for restoring to the initial level and improving the filtration properties of rocks contaminated with drilling fluids.

2. Problem statement

Drilling muds play an important role in ensuring the growth of drilling volumes and hydrocarbon production. Contamination of the bottomhole formation zone of the formation during primary and secondary opening and the associated deterioration of natural reservoir properties can lead to a significant loss of well productivity and, conversely, minimization of such contamination can allow obtaining industrial products from deposits, the production of which, even recently, was impossible for technical or economic reasons [5–9].

A significant contribution to research of the fundamental physico-chemical processes occurring in the wellbore and in the area around it, in relation to the issues of the stability of the shaft, the hydrodynamics of flushing and cleaning of the outcrop, and the qualitative opening of productive horizons were made by number of researchers. The development of these provisions regarding the conditions of drilling wells in the deposits of Ukraine is reflected in [7, 8]. These scientists have developed and implemented a large number of various formulations of drilling muds aimed at effective drilling of wells and high-quality opening of productive horizons in difficult mining and geological conditions.

According to modern ideas, clay-free biopolymer systems provide the highest quality of opening productive horizons among water-based drilling muds [10–12]. This is due to the biodegradable polysaccharide composition and acid-soluble solid phase, as well as unique rheological, structural-mechanical and filtration properties. In addition, clay-free biopolymer drilling muds create almost no man-made load on the environment, ensure successful passage of horizontal and inclined wells, uncomplicated opening of zones with abnormally low formation pressures, avoidance of scree, absorption and differential adhesions.

For carbonate-type collectors, which are typical for the gas condensate field of the Zahoryanska area of the Dnieper-Donetsk rift, it is advisable to use a polymer-potassium low-clay type, a clay-free polymer-magnesium type liquid on a polyacrylamide basis, and a hydrogel-magnesium type liquid using bischofite.

The use of bischofite solutions as part of flushing fluids is promising. Estimated resources of bischophite only within the Orchykiv depression of the Dnieper-Donetsk rift amount to about 10 billion tons. In practice, the use of bischofite at gas production enterprises is often limited due to its irrational use. Salt deposits, when bischophite enters the formation, can form in the pores of the rocks of the bottomhole formation zone, reducing their permeability and porosity [13, 14]. The chemical composition of inorganic deposits is represented mainly by calcium sulfates and carbonates, oxides, carbonates, oxides, and iron sulfide [10, 11].

The main reasons for the formation of salts are:

- a decrease in pressure and an increase in the temperature of mining fluids, which leads to the release of dissolved carbon dioxide into the gas phase:

$$Ca^{2+} + 2(HCO_3^-) \rightarrow CaCO_3 \downarrow + CO_2 \uparrow + H_2O;$$

- mixing of incompatible waters:

$$Ba^{2+}(Sr^{2+}, Ca^{2+}) + SO_4^{2-} \rightarrow BaSO_4 \downarrow (SrSO_4, CaSO_4);$$

- supersaturation of fluids is limited by soluble salts and their salting out.

Considering the above, there is a need to study the influence of flushing fluids on the capacity-filtration characteristics of carbonate rocks and to improve the method of preparing bischofite solution for use as part of flushing fluids when drilling wells.

The main direction of research was to determine the type of liquid that will be used as a flushing agent in carbonate-type rocks and at the same time will maximally preserve the capacity-filtration properties of the pore space.

3. Materials and methods

The following drilling muds were studied: polymer-potassium low-clay type fluids, clay-free polymer-magnesium type fluids on a polyacrylamide basis, and hydrogel-magnesium type fluids.

The influence of the flushing fluid on the properties of carbonate rocks was evaluated according to the standard methodology at the UDPK-1M installation (figure 1).

The research was carried out on carbonate core material taken from the drilling interval 4935 – 5090 m of well №1 of the Zahoryanska area, which corresponds to the interval of well №3, which needs to be opened. Before conducting the research, the core was wetted with formation water of the chlorcalcium type ρ=1.18 g/cm^3, typical for deposits B24-25 of the Zahoryanska field. Repression on the formation during the research was 250 – 300 atm, that is, the conditions of maximum repression on the formation under dynamic loads during the drilling process were modeled.

According to some data, under the influence of process fluids based on bischofite, the filtration properties of the reservoir often deteriorate due to the formation of insoluble sulfate deposits in the pore space as a result of the interaction of filtrates and reservoir fluids [2]. In the second series of experiments, the effect of the presence of sulfate ions in bischophyte on the properties of carbonate collectors was studied. In order to detect the process of pore blocking by chemically formed gypsum, the core was wetted with formation water of chlorcalcium type ρ=1.18 g/cm^3. Up to 20 volumes of the pore space of purified and untreated bischofite ions SO_4^{2-} were passed through the core.

Bischofite solutions with a mass fraction of $MgCl_2$ of 24% from well №1 of the Zahoryanska area were used for research. The chemical macro-composition of bischofite solutions from well №1 of the Zahoryanska field is presented in table 1.

In order to find components that accelerate the precipitation of gypsum deposits, studies were conducted to determine the effect of surface-active substances on the process of calcium sulfate deposition.

Studies were conducted with surface-active substances: 1) KI-1-M – a mixture of catapin and urotropin; 2) SRK – aqueous solution of sulfur adduct of saturated fatty alcohol; 3) EM-1 – an aqueous solution of cationic and amphoteric surfactants; 4) Stentex – cationic surfactant; 5) CAPB – cocamidopropylbentain belongs to amphoteric surface-active substances.

Before conducting the experiment, $Na_2SO_4 \cdot 10\,H_2O$ was added to the bischofite solution with a mass fraction of $MgCl_2$ of 24% at the rate of 28.38 g/dm^3. In a measuring cylinder with a volume

Figure 1. Permeability test setup core in reservoir conditions (UDPK-1M).

of 100 ml, the necessary amount of the prepared solution of bischofite with a mass fraction of $MgCl_2$ of 24% and with an additive of surfactant concentration of 0.1% was placed. The calculated amount of calcium chloride dried to a constant mass was added to the solution. Some time, after the initial turbidity, massive spontaneous formation of solid phase nuclei occurred. At

Table 1. Chemical macro-composition of bischophyte solutions from well №1 of the Zatyryno field.

Cations	**C, g/l**	**w, eq. %**	**Anions**	**C, g/l**	**w, eq. %**
Potassium + Sodium	1.0610	0.58	Chlorine Sulfine	273.04 11.65	69.90 3.05
Calcium	2.0000	1.26	Carbonate	–	–
Magnesium	94.8480	98.16	Hydrocarbonate	0.20	0.05
Total	97.9090	100.00	Total	284.90	100.00

this stage, the contents of the measuring cylinder were mixed. After the onset of sedimentation, stirring was stopped and further sedimentation took place under static conditions.

The resulting solutions were kept in a thermostat at a temperature of 20 ℃ for 168 hours. The content of sulfates in the sediment was determined by the gravimetric method. After 7 days, the sediment was filtered through a "blue tape" filter, decanted, washed with hot distilled water until there was a negative reaction to the chloride ion. After that, the filter was dried on a tile in a crucible, charred in a crucible furnace at a temperature of 500 ℃, fired at a temperature of 800 ℃ and weighed after cooling. The degree of deposition of calcium sulfate X in % was determined by formula 1:

$$X = \frac{m}{m_0} \cdot 100\%, \tag{1}$$

where m – is the mass of calcium sulfate in the sediment, g; m_0 – is the mass of calcium sulfate, which corresponds to the initial concentration of sulfate ions in the solution, g.

At the same time, the nature of the deposition was visually determined by the change in the volume of the sediment and the structure of the crystals under an Olympus BX 41 microscope (2005, Japan) with a magnification of 100 times.

4. Experimental laboratory results

From the conducted research, it can be concluded that solutions of clay-free polymer-magnesium type on polyacrylamides have the greatest depth of penetration into the formation. At the same time, they are characterized by a low coefficient of reservoir recovery. In addition, after processing the core with an acid solution, insoluble polymer structures are formed, which almost completely calm the formation.

Solutions of the polymer-potassium type, although they have a small penetration depth, but this effect is achieved by calming the pores with a solid insoluble clay phase, which is part of these solutions. Due to this, the formation recovery rate after using such solutions is also low.

Solutions of the hydrogel-magnesium type, with a relatively small depth of penetration into the formation, are distinguished, among others, by a high coefficient of recovery of permeability. After the application of such solutions and subsequent acid treatment, the pore space of the formation is almost completely restored. They do not contain an introduced solid phase that would irreversibly calm the pore space. Carbonate blockers are formed during the preparation of this flushing fluid and do not calm the pore space.

Table 2 presents the results of studies of the influence of flushing fluid on the capacity-filtration characteristics of carbonate rocks.

Bischophyte is a component of the investigated solutions. A study of the influence of the presence of sulfate ions in bischophyte on the properties of carbonate reservoirs was carried out. The influence of sulfate ions on the permeability and recovery coefficient of the carbonate core is shown in Table 3. It is noted that in the presence of sulfate ions in bischofite, the permeability

Table 2. Results of studies of the influence of flushing fluid on the capacity-filtration characteristics of carbonate rocks.

Flushing fluid	The depth of maximum permeability of solution into reservoir, cm		Recovery coefficient for the fractured collector, %	
	in the matrix collector	in fractured reservoir	without acid treatment	followed by acid treatment
Polymer-potassium solution with a solid phase	10-15	30-40	18-25	–
Clay-free polymer-magnesium solution	15-18	45-60	15-30	3-7
Hydrogel-magnesium solution	12-17	40-50	70-85	92-98

Table 3. The influence of sulfate ions on permeability and recovery indicator of carbonate core.

Drilling mud	Permeability, md	Recovery indicator of carbonate core, %
Bischofit with sulfate ions	26.50	93.90
Bischofit with sulfate ions + formation water	1.62	6.20
Bischofit without sulfate ions	20.59	96.47

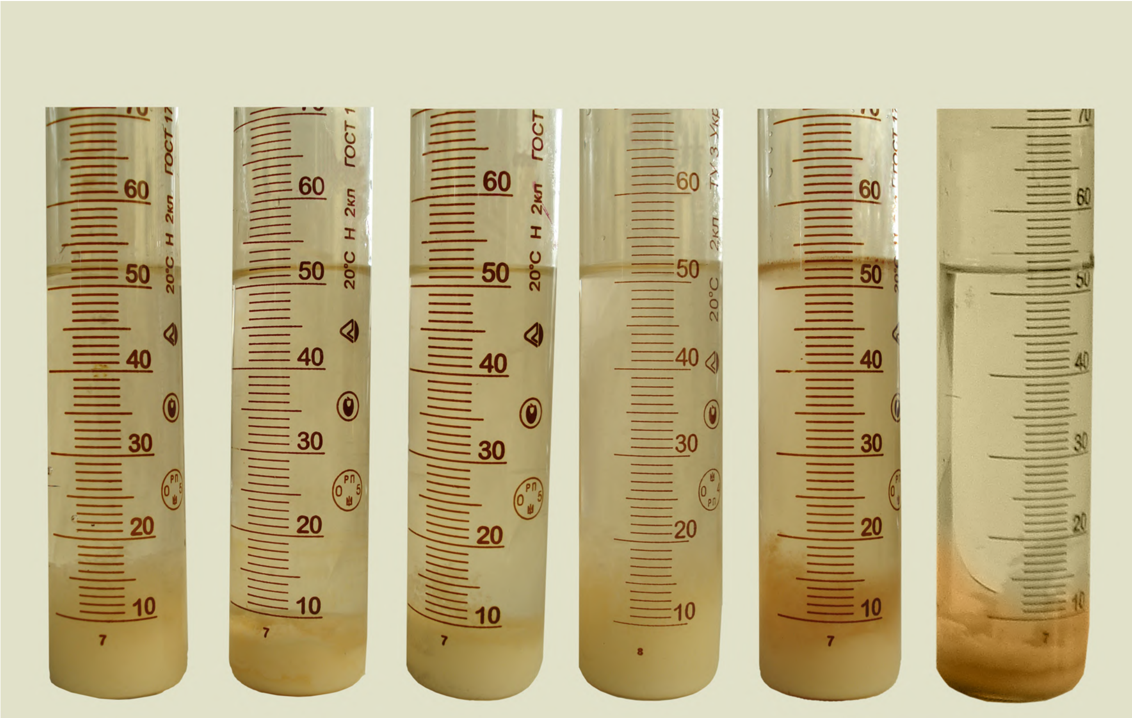
and recovery of the formation in the presence of formation water decreases by 11.53, and when using pure bischofite – by only 1.29 times.

Thus, as the research results showed, it is not necessary to use desulfated bischofite for the preparation of polymer-magnesium solutions. To solve this problem, it is necessary to use precipitation catalysts, which make it possible to simultaneously carry out rapid desulfation of bischofite and prevent salting out of chlorides. The crystallization of calcium sulfate from an aqueous solution of bischofite with a mass fraction of $MgCl_2$ of 24% in the presence of surface-active substances was investigated. The processes of calcium sulfate crystallization in the presence of various surface-active substances differ significantly (figure 2) [15, 16].

In figure 3 shows unwashed and washed from chloride precipitates on the filter. Precipitates with the addition of amphoteric surfactants have a visually smaller volume compared to the control experiment, and those with the addition of cationic surfactants have a more fragile structure and large crystals.

In the unwashed sediment formed from pure bischofite, without the addition of surfactant, a group of closely spaced crystals of various shapes is formed. Addition of cationic surfactants (KI-1M, St) to the initial solution leads to a decrease in extraneous formations and the precipitation of needle-like crystals of different lengths.

The structure of calcium sulfate crystals without the addition of surfactants and with the addition of cationic surfactants is approximately the same. Crystals are needle-shaped and vary in length. However, the addition of amphoteric surfactants (EM and CAPB) and cationic surfactant SRK leads to the formation of larger lamellar crystals, the diameter and thickness of which increase significantly, and the length decreases (figure 4).



1 2 3 4 5 6

Figure 2. Sedimentation in bischofite solution with a mass fraction of $MgCl_2$ 24% during elimination of sulfates in the presence of surfactants, the mass fraction of which is 0.1%: 1 – without surfactants; 2 – EM; 3 – SRK; 4 – St; 5 – KI-1M; 6 – CAPB.

After calcination of the precipitate at a temperature of 800 ℃, the structure of the crystals with different additives of surfactant and the control experiment is approximately the same.

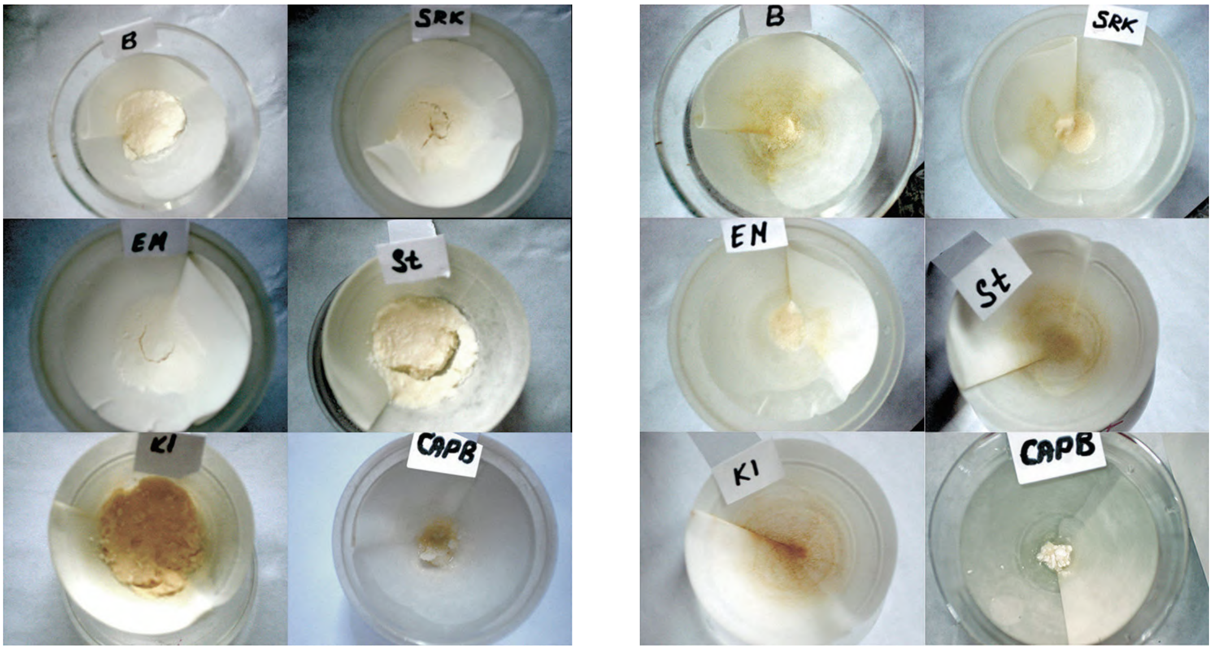
The positive effect of surfactant additives is obvious, since in the presence of these reagents the sediment is formed in the form of a fine dispersion, which, unlike amorphous sediment, can be easily removed from the container where bischofite desulfation takes place.

As can be seen from table 4, the degree of precipitation of calcium sulfate from an aqueous solution of bischofite with a mass fraction of $MgCl_2$ of 24% in the presence of surface-active substances (w = 0.1%) decreases in the following order: CAPB > EM > SRK > St > KI-1M, and the sediment volume, on the contrary, increases in this order.

The lower value of the calcium precipitation degree of sulfate relative to the volume of sediment in the presence of St and KI-1M can be explained by the fact that the process of salting out chlorides prevails over the chemical reaction of precipitation of sulfates.

Analysis of the influence of the amount of precipitant on the rate of separation of solid and liquid phases showed that EM, CAPB and SKR surfactants also have close results in terms of the rate of precipitation. Phase separation takes place within 0.5–1 h, the solid phase settles to the bottom of the vessel, a clear separation boundary between the phases is visible. Over time, the volume of sediment does not increase, and after 5 days its compaction is observed. In the presence of cationic surfactants KI-1M and St, phase separation occurs very slowly, the sediment is loose, occupies 2/3 of the cell volume.

The results of the study showed that the excess introduction of precipitant $CaCl_2$ by more than 4 times in the presence of all surface-active substances leads to a decrease in the degree of precipitation of $CaSO_4$, while the volume of the precipitate does not change.



a b

Figure 3. Filter residue: a – unwashed; b – washed from chlorides.

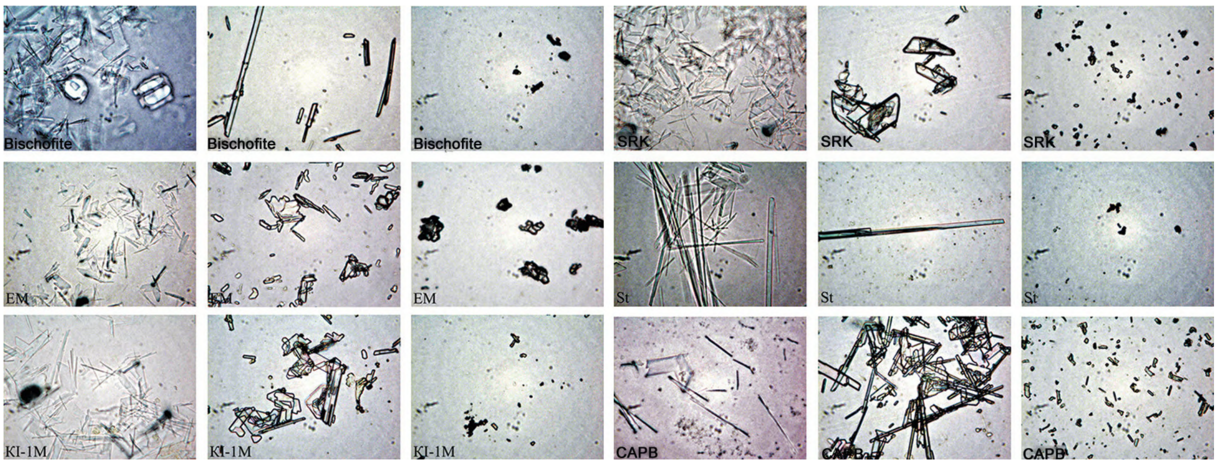


Figure 4. The structure of sediment crystals (mass fraction of surfactant – 0.1%).

The results of the experiments show that among the investigated surface-active substances EM, CAPB and SKR are effective catalysts of sulfate precipitation and inhibitors of salting out chlorides. Therefore, in order to accelerate the process of precipitation of $CaSO_4$ during the desulfation of bischofite intended for the preparation of the flushing fluid of the primary opening of the carbonate deposits of the Zahoryanska area of well № 3, the catalyst cocamidpropylbentaine was used. Due to the addition of this reagent in a volume of 0.1% to bishofite at the time of introduction of calcium chloride, the precipitation process was accelerated four times. Thus, the precipitate of $CaSO_4$ in bischofite without the addition of a catalyst was formed in a vertical container with a volume of 36 m^3 for 20 days, and with a catalyst – for 5 days.

In addition, in order to fully use the $CaCl_2$ introduced into the first portion of bischofite, at the

Table 4. The influence of the amount of precipitant on the degree of calcium sulfate of precipitatio in the presence of surfactants (w=0.1%).

Surroundings	Surfactant	Mass fraction of calcium chloride, 1%					
		1		6		10	
		Sediment volume, %	The degree of precipitation of $CaSO_4$, %	Sediment volume, %	The degree of precipitation of $CaSO_4$, %	Sediment volume, %	The degree of precipitation of $CaSO_4$, %
Bischofite solution ($w(MgCl_2)=24\%$)	–	20.00	5.60	29.02	12.10	30.10	15.21
	KI-1M	16.92	1.60	23.07	3.60	24.60	2.66
	St	23.08	4.80	38.46	10.30	39.50	6.37
	SKR	3.08	19.96	13.84	48.20	15.20	49.54
	EM	3.01	28.65	12.30	68.20	13.80	49.51
	CAPB	1.50	40.31	3.08	88.96	3.90	62.34

rate of 4 tons per 140 m^3, i.e. in a fourfold excess in relation to the content SO_4^{2-} in bischofite, the second portion of desulfurization of bischoffite was carried out by introducing 0.1% into non-desulphated bischoffite cocamide-probilbentaine and $CaSO_4$ sediment, which, according to chemical analysis, contained up to 100 g/l of ions Ca^{2+}, which made it possible to speed up the desulfation process and ensure maximum purification of bischofite from sulfate ions.

Thus, in industrial conditions, for the first time, the catalyst for the precipitation of $CaSO_4$ during the desulfation of bischofite was tested and the technology of preparation of bischoffite was applied by reusing $CaSO_4$ sediment with an excess content of $CaCl_2$, which made it possible to reduce the cost of the preparation process and accelerate the precipitation by 4 times.

5. Conclusion

Based on the above, the following conclusions can be drawn:

1. Hydrogel-magnesium fluids using desulfurized bischofite are the optimal flushing fluid for opening carbonate-type formations.
2. The opening of productive layers in depressions using a solution of desulfurized bischofite allows to preserve the natural filtering properties of the collectors and increase the efficiency of extraction of hydrocarbons from the subsoil. In the presence of sulfate ions in bischophyte, the permeability and formation recovery in the presence of reservoir water decreases by 11.53 times, and when using pure bischophyte – only by 1.29 times.
3. When preparing bischofite, it is recommended to use the amphoteric surfactant CAPB as a catalyst for precipitation of sulfates and an inhibitor of salting out chlorides at a mass fraction of 0.1%. This makes it possible to increase the degree of precipitation of $CaSO_4$ by 76.86%, to reduce the volume of the formed sediment by 9.4 times.
4. Industrial tests showed that the preparation of bischofite solution using CAPB ensures a 4-fold reduction in bischofite preparation time, a 7.5-fold increase in the degree of calcium sulfate removal, and a 3-fold decrease in sediment volume.

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References

[1] Puhach V 2014 *Ekonomika pryrodokorystuvannia i okhorony dovkillia* 45–48 URL http://dspace.nbuv.gov.ua/handle/123456789/166641
[2] Pysmennyi S, Fedko M, Shvaher N and Chukharev S 2020 *E3S Web of Conferences* **201** 01022 URL https://doi.org/10.1051/e3sconf/202020101022
[3] Shvaher N, Komisarenko T, Chukharev S and Panova S 2019 *E3S Web of Conferences* **123** 01043 URL https://doi.org/10.1051/e3sconf/201912301043
[4] Markevych K and Omelchenko V 2016 *Hlobalni enerhetychni trendy kriz pryzmu natsionalnykh interesiv Ukrainy* (Kyiv: Zapovit) URL https://razumkov.org.ua/images/broshura/2016_ENERGY-S.pdf
[5] Lipatov E Y and Krivova N R 2019 *IOP Conference Series: Materials Science and Engineering* **663** 012066 URL https://doi.org/10.1088/1757-899X/663/1/012066
[6] Kotskulych Y S and Kotskulych Y Y 2008 *Rozvidka ta rozrobka naftovykh i hazovykh rodovyshch* **2** 93–96
[7] Raptanov A K, Ruzhenskyi V V, Kostiv B I, Myslyuk M A and Charkovskyy V M 2021 *SOCAR Proceedings* **2** 52–64 URL https://doi.org/10.5510/OGP2021SI200573
[8] Myslyuk M and Zholob N 2021 *Upstream Oil and Gas Technology* **7** 100056 ISSN 2666-2604 URL https://doi.org/10.1016/j.upstre.2021.100056
[9] Myslyuk M A, Salyzhyn Y M and Bogoslavets V V 2014 *Neft. khozyaystvo - Oil Ind.* **1** 36–40
[10] Baba Hamed S and Belhadri M 2009 *Journal of Petroleum Science and Engineering* **67**(3) 84–90 ISSN 0920-4105 URL https://doi.org/10.1016/j.petrol.2009.04.001
[11] Nwosu O U and Ewulonu C M 2014 *J. Polym. Biopolym. Phys. Chem.* **2**(3) 50–54 URL https://www.researchgate.net/publication/280599858
[12] Chudyk I I, Bohoslavets V V and Dudych I F 2016 *Rozvidka ta rozrobka naftovykh i hazovykh rodovyshch* **4**(61) 34–42
[13] Dmytrenko V I, Zezekalo I G and Vynnykov Y L 2022 *IOP Conference Series: Earth and Environmental Science* **1049**(1) 012052 URL https://doi.org/10.1088/1755-1315/1049/1/012052
[14] Dmytrenko V, Vynnykov Y and Zezekalo I 2020 *E3S Web Conf.* **166** 06005 URL https://doi.org/10.1051/e3sconf/202016606005
[15] Kudriashov S Y 2006 *Management of Salt Deposition in Oilfields* (NK Rosneft)
[16] Semyn V Y 1989 Byshofyt – odyn yz ynhybytorov hydratoobrazovanyia *Nauchn. tr. VNYYhaz* Nauchno-tekhnycheskyi prohress v tekhnolohyy kompleksnoho yspolzovanyia resursov pryrodnoho haza (Moskow: VNYYhaz) 79–82

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Improvement of terrestrial storage-shelter facilities for natural gas storage as part of gas hydrates

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Improvement of terrestrial storage-shelter facilities for natural gas storage as part of gas hydrates

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Abstract. Natural gas in the gas hydrates form is proposed to be stored in improved shell gas-resistant structures. The improvement of the construction and the operation method of these buildings consists in the use of liquid foam as a thermal insulation material. The design and operation technology of a terrestrial shelter facility for the accumulation and storage of natural gas as a gas hydrate is proposed, the main element of which is a frameless gas-resistant shelter in the form of at least two dome-shaped gas-tight soft shells on a thermally insulated base, the space between which is filled with liquid foam. The use of these hydrate shelters will significantly increase the efficiency and competitiveness of natural gas storage technology in the gas hydrates form.

1. Introduction

As is known, at relatively low temperatures and a certain pressure, water molecules form a three-dimensional structure that can be occupied by gas molecules (for example, methane, ethane, carbon dioxide, etc.) [1]. This type of compounds are known as clathrates or inclusion compounds [2]. Today, a number of technologies are known in which gas hydrates are an intermediate or target product. These are the so-called gas hydrate technologies (transportation and storage of natural gas in gas hydrate form [1], gas hydrate fractionation, concentration using gas hydrates of any aqueous solutions [3, 4], etc.).

At the same time, the natural gas storage in gas hydrate form in many cases becomes a real alternative to traditional technologies.

Storage of gas hydrate requires maintenance of appropriate thermobaric conditions. However, gas hydrate can exist in a metastable state for some time as a result of the self-preservation effect or due to preservation by a ice layer of [4–6].

In addition, a compulsory condition for the reliable gas hydrate storage is the organization its high-quality thermal insulation and sealing. Such conditions should be ensured in specialized hydrate shelters. There are a number of projects, which involve the use of surface or partially buried capital structures built from traditional building materials.

However, warehouses made of traditional metal or reinforced concrete structures cannot provide effective sealing and thermal insulation. In fact, these structures can only perform the role of a skeleton for attaching insulating and sealing elements. At the same time, a relatively thin layer of porous material (foam, mineral wool, etc.) can provide effective thermal insulation, and a polymer film can provide high-quality sealing [7, 8].

Based on this, it is proposed to use gas-resistant pneumatic structures as hydrate storages [9]. At the same time, modern coatings allow maintaining their operational characteristics for a long time (up to 15-20 years) [10]. In addition, they can be easily dismantled, transported and quickly assembled, that is, they can be considered as mobile technological objects.

These buildings are structures supported by a gas cushion. However, the pressure in them is higher than atmospheric only to ensure the force for the formation of a dome-shaped form and to compensate for the mass of the shell itself (in the range of pressure – 0.01-1.0 MPa) [11, 12].

However, the thermal resistance of such structures is insignificant [11]. Therefore, they need their conditioning (cooling). Taking into account the costs of cold production, it is impractical to operate such buildings without the organization of additional thermal insulation. A variant of increasing the thermal resistance of these structures is the use of two- and three-layer coatings. However, the thermal resistance of the barrier gas layer increases noticeably only up to its thickness of 0.3 m [9]. For example, the coefficient of thermal conductivity of the two-layer shelters considered in [11] was 2.8-3.4 $W/(m^2 K)$. Therefore, regardless of the external temperature, a significant heat flow will enter the storage even through a double-layer coating.

2. Improvement of the storage-shelter thermal insulation system

It is known that the thermal insulation properties of materials are determined by their porosity. The pores are filled with gas of low thermal conductivity. As thermal insulation, among others, materials are used, which are polymers, foamed before the start of hardening. Hardening, in this case, is required for the production of heat-insulating panels of a certain shape and size for the convenience of their use and transportation.

However, the phase state of material bubbles does not affect its thermal insulation properties. Therefore, the use of solid porous thermal insulation materials is due to the convenience of their use. In the case of gas-resistant shell structures, the use of solid heat-insulating materials will be unacceptable, as this will significantly complicate the construction and duration of the shelter installation.

Therefore, it is suggested to use liquid polymer foams as a material for thermal insulation of gas-resistant shell structures – shelters for gas hydrates. At the same time, in the case of using a transparent shell-shelter, the foam will allow part of the scattered sunlight into the storage-shelter. This will make it possible to regulate the supply of energy to the storage to some extent. The schematic diagram of such a storage-shelter, supplemented by a complex of appropriate equipment for the implementation of the technological process of gas hydrate storage and regasification, is presented in figure 1.

Its main elements are shelter, base and auxiliary equipment. The shelter of the hydrate storage-shelter consists of a liquid foam layer between several impermeable to gas and water canvases 2 and 4 with a sun-reflective layer on top.The shelter is fixed by a net made of ropes 5. The storage-shelter is equipped with the following systems: foam generation and selection of products its destruction; storage conditioning (cooling and heating); gas and water selection.The foam generation system involves supplying the produced foam to the upper part of the space between the inner and outer shells. At the same time, a system for selecting of foam destruction products is placed between the shells at the base level.

For the maximum energy efficiency of the technology, the level of gas hydrate cooling in the production process is determined, taking into account the duration and parameters of transportation and storage.

The flow of thermal energy from the ground through the base of the storage at its average value of 17 W/m^2 [13] will be 0.03 MW. Thermal insulation of the base will allow to reduce it to 9 kW. After the preparation of the site, the base of the storage-shelter is arranged by sequentially laying a layer of thermal insulation 9 (figure 1), a coating of water- and gas-tight material 8, a heat exchanger in the form of a system of pipes 16, a system of gutters and perforated pipes 6

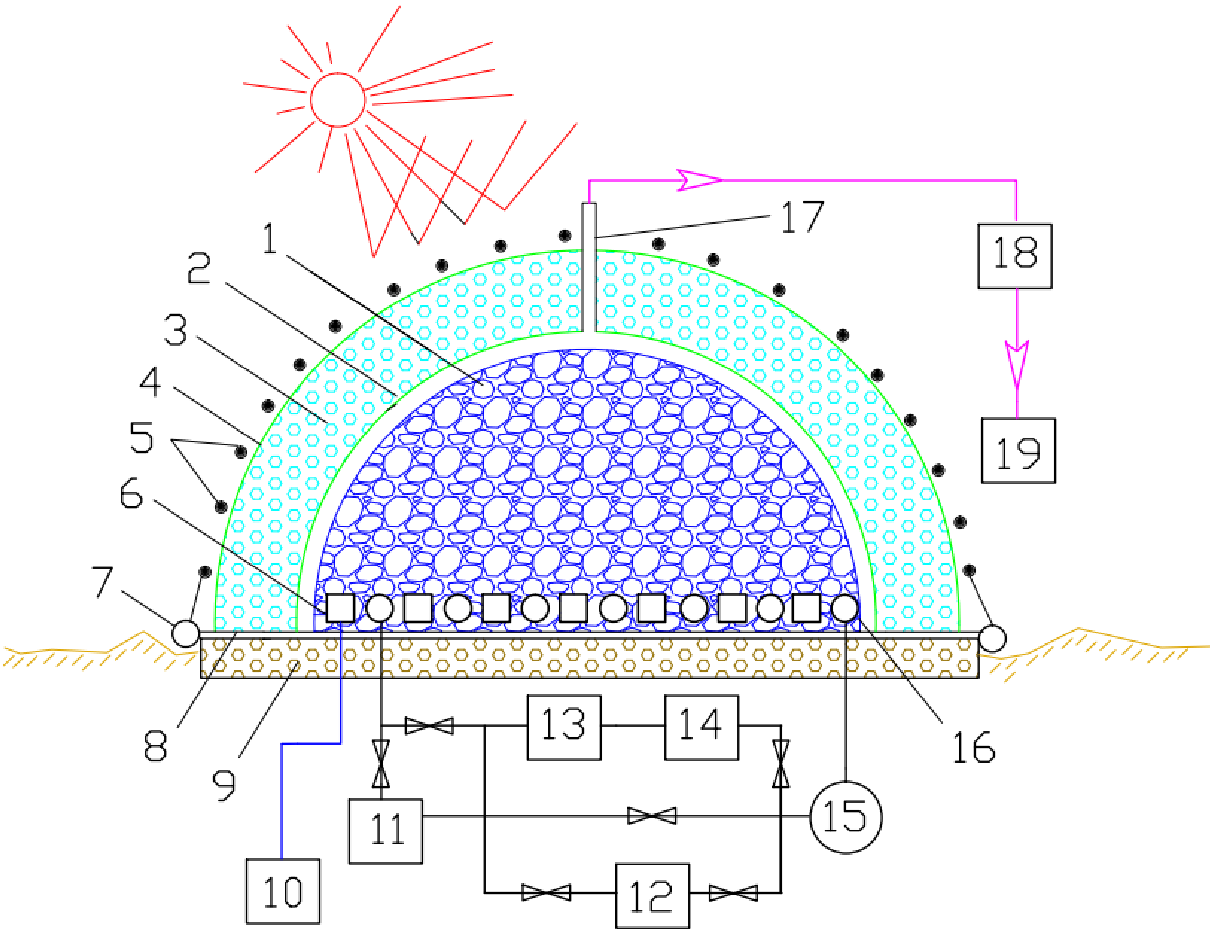

Figure 1. Schematic diagram of hydrate storage-shelter at the gas hydrate storage stage: 1 – gas hydrate; 2 – the lower fabric for the shelter; 3 – a liquid foam layer; 4 – the upper fabric for the shelter; 5 – a system of external reinforcement of the shelter in the form of a net made of ropes; 6 – perforated pipes of the gas and water extraction system from under the gas hydrate stack; 7 – a hermetic connection system of the cover sheets and the base; 8 – base covering made of material impermeable to gas and water; 9 – heat-insulating coating of the base; 10 – water collection tank; 11 – system of heating the coolant based on the solar collector; 12 – coolant heating block; 13 – unit of the refrigerating unit; 14 – air cooling system; 15 – circulation pump; 16 – heat exchanger pipe system; 17 – gas selection system; 18 – gas compression unit; 19 – gas consumer [9]

for the removal of gas and water.

For reliable sealing of the hydrate storage-shelter, system 7 seals the connection between the shelter sheets and the base. The isolated space formed is connected to the compressor 18 by the gas discharge line 17. The temperature regime of the hydrate storage is ensured by the accumulated cold in the gas hydrate and the additional air conditioning system. Hydrate dissociation is proposed to be carried out directly in the storage at the expense of solar energy. The temperature of the gas hydrate (cooling during storage and heating in the process of gas extraction) is maintained by pumping the cooled or heated coolant through the heat exchanger 16 at the base of the hydrate storage-shelter.

The coolant is cooled by a refrigerating unit 13 or an air cooling system 14. Cooling or

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heating of the coolant is carried out in the solar collector 11, heater 12, refrigerating unit 13, air cooling system 14. Gas selection is carried out as a result of controlled dissociation of gas hydrate when pumping the coolant through the heat exchanger 16. Water is discharged from the storage-shelter to the tank 10 by the collector 6. (In addition, it is possible to organize the inflow of solar energy through the transparent areas of the shelter).

Gas through the selection line 17 enters the compression unit 18. Then it is consumed by the gas distribution network. The pressure in the line is limited by the mechanical strength of the shelter and lies within 0.2-0.4 MPa. The mobility of the storage-shelter will allow them to be placed directly near the objects of consumption. This will allow the gas during pressure dissociation to be sent to the gas distribution network without additional compression.

3. Calculation of storage-shelter operational parameters

The thermal resistance of the coating, which characterizes the heat-shielding characteristics of the gas-resistant storage-shelter, is determined by the formula:

$$R_{stor} = \frac{1}{\alpha_1} + \frac{2 \times \delta_{shel}}{\lambda_{shel}} + R_{barr} + \frac{1}{\alpha_2},$$

where R_{stor} – reduced thermal resistance of the storage-shelter shell, m^2 K/W; α_1, α_2 – coefficients of heat transfer of external and internal air, respectively,W/K m^2;δ_{shel} – thickness of the gas-tight shell fabric, m; R_{barr} – thermal resistance of the barrier layer, m^2 K/W; λ_{shel} – coefficient of thermal conductivity of the shell fabric, W/m K.

The average temperature for the forest-steppe zone of Ukraine for January is 265 K, July – 293 K [14], [15]. The thermal resistance of the storage-shelter cover R_{stor} in summer will be 0.27 m^2 K/W, in winter – 0.35 m^2 K/W. Then, during the winter period, energy will flow into the storage-shelter:

$$q_w = \frac{1}{R_{stor}} \times (t_{out} - t_{instor}),$$

where t_{tout},t_{instor} – air temperature, respectively, outside and in the storage-shelter, K.

$$q_w = \frac{1}{0.35 \times (265 - 248)} = 48.6.$$

The heat flow in the hydrate storage in the summer (q_s) will be [16]:

$$q_s = q_{av.d} + kA_d = \frac{1}{R_{stor.s}}(((t_s + \frac{p_{rad} \times I_{rad}}{\alpha_{surf}}) - t_{instor}) + K(0,5AK_m + \frac{p_{rad}(I_m - I_{rad})}{\alpha_{surf}})),$$

$$q_s = 150.0,$$

where A_d – daily fluctuation of heat energy flow, W/m^2; $q_{av.d}$ – average daily heat energy input to the storage, W/m^2; k – daily coefficient of change of heat flow A$_d$; t_s, t_{instor} – the temperature of the outside air in July and inside the storage, respectively, K; p_{rad} – coefficient of absorption of heat of solar radiation by the external surface of the storage; I_{rad} – average daily amount of solar radiation reaching the storage surface in the warmest month, MJ/m^2; α_{surf} – coefficient of heat absorption of the external surface of the storage for the warm period of the year; K_m – the maximum amplitude of daily air temperature fluctuations in the warmest month of the year, K; I_m, $I_{av.d}$ – maximum and average daily value of the amount of solar radiation, respectively, MJ/m^2.

The results of calculations of thermodynamic parameters for gas hydrate storage in a storage-shelter with a two-layer coating and an air barrier layer are given in table 1.

Table 1. Gas hydrate storage parameters in a double-layered storage with an air barrier layer.

Thermodynamic parameters	Winter	Summer
Thermal resistances, R_{stor}, m^2 K/W:	0.35	0.27
Heat flow to gas hydrate without thermal insulation layer, q, W/ m^2	48.6	105.0

Taking into account the thermal resistance, the thermal inertia of the two-layer cover of the hydrate reservoir will be [11]:

$$D_{ther.in} = 0.27 R_{stor} \sqrt{\lambda \rho c},$$

where $D_{ther.in}$ – thermal inertia; R_{stor} – thermal resistance, m^2 K/W.

$$D_{ther.in} = 0.27 \times 0.27 \sqrt{0.0244 \times 1.29 \times 717} = 0.4; D_{ther.in} < 1.5$$

Therefore, such a coating is inertialess. Let's consider the option of reducing the heat flow through a two-layer coating when filling the space between them with stable foam (foam density 4.0 kg/m^3, layer thickness δ_{coatl} – 1.5 m, coefficient of thermal conductivity λ_{coatl} – 0.041 W/(m·K)) using an example storage with a capacity of 3,000 tons of gas hydrate (5.4 million cubic meters of natural gas).

The coefficient of thermal conductivity λ_{coatl} of a two-layer reinforced coating with a thickness of 2 mm is 0.16 W/m K [16]. Then its thermal resistance R coat1 will be at the level of 0.0125 m^2 K/W. The thermal balance of the storage-shelter is described by the equation:

$$Q_1 + Q_2 - Q_3 - Q_{add} = 0,$$

where Q_1 – heat flow into the storage through the shell, J; Q_2 – heat flow from the base of the storage, J; Q_3 – cold accumulated by gas hydrate, J, Q_{add} – additional heat removal (cooling), J.

The reduced thermal resistance of the coating is determined by the formula:

$$R_{stor.coat} = \frac{1}{\alpha_{out}} + \frac{2 \times \delta_{coat1}}{\lambda_{coat1}} + \frac{\delta_{coat2}}{\lambda_{coat2}},$$

where $R_{stor.coat}$ – reduced thermal resistance of the storage-shelter shell, m^2 K/W; α_{out} – coefficients of heat transfer of outside air, W/K m^2; δ_{coat1} – coating layer thickness, m; λ_{coat1} – thermal conductivity coefficient coating, W/m K; δ_{coat2} – thickness of the foam layer, m; λ_{coat2} – coefficient of thermal conductivity of the foam layer, W/m K.

Therefore, the reduced thermal resistance of the storage-shelter cover ($R_{stor.coat1}$ and $R_{stor.coat2}$) for winter and summer will be 37.78 and 37.62 m^2 K/W, respectively. Then, in winter, the heat flow into the storage from the outside will be:

$$q_{w1} = \frac{1}{R_{stor.coat1}} \times (t_{out} - t_{instor}),$$

where t_{tout},t_{instor} – air temperature, respectively, outside and in the storage, K.

$$q_{w1} = \frac{1}{37.78 \times (265 - 248)} = 0.45.$$

The total heat flow into the storage-shelter through the coating (Q_{w1}) in the winter period will be 1.76 kW.

The heat flow to the storage in the summer (q_{s1}) was determined by the formula:

$$q_{s1} = \frac{1}{R_{stor.coat2}} \left(t_{out} + \frac{p_{rad} \times I_{rad}}{\alpha_{surf}} - t_{instor} + K \left(0.5AK_m + \frac{p_{rad}(I_m - I_{rad})}{\alpha_{surf}} \right) \right),$$

$$q_{s1} = 1.33,$$

The total heat flow into the storage through the coating (Q_{s1}) in the summer period will be 5.23 kW.

The heat flow that enters the gas hydrate from the base (Q_2), with its average annual value for mid-latitudes of 0.17 W/m^2 [15], will be 0.3 kW. Its insulation will reduce heat input to 0.25 kW.

In the table 2 shows a comparison of the calculated parameters of gas hydrate storage in ground-based gas-resistant storages in variants of the air layer between shells and foam.

Table 2. Comparison of gas hydrate storage parameters in ground gas-resistant storage-shelters depending on the level of thermal insulation.

Thermodynamic parameters	Winter	Summer
Thermal resistances, $R_{stor.coat}$, m^2 K/W:		
– air between the fabrics of the shell	0.27	0.35
– a layer of foam between the fabrics of the shell	37.78	37.62
Heat flow to storage-shelter, q, W/m^2:		
– air between the fabrics of the shell	48.6	48.6
– a layer of foam between the fabrics of the shell	0.45	1.33
Heat flow to storage-shelter, Q_1, kW:		
– air between the fabrics of the shell	189	408.0
– a layer of foam between the fabrics of the shell	1.76	5.23
Energy costs for cooling, Q_3, kW:		
– air between the fabrics of the shell	190.2	409.2
– a layer of foam between the fabrics of the shell	2.1	5.5

Therefore, the required capacity of the additional cooling system of the storage-shelter for storage of gas hydrate without its dissociation (at a temperature of 258 K) is 0.9 kW in the winter period, and 4.44 kW in the summer period.

4. Modeling of heat exchange processes

Let's set the temperature on the surface of the gas hydrate as a result of the arrival of heat flow, as a process of heat transfer through a multilayer coating. On one side of the coating is the external environment with a temperature of T_p, and on the other – cooled to a temperature of T_g gas hydrate (figure 2).

Formulation of the problem. Let's assume: the initial temperature of the gas hydrate (T_0) is 248 K; the gas hydrate stack has the shape of a hemisphere with a base radius (R_g) of 23.5 m; the surface of the gas hydrate is covered with a 1.5 m layer of foam ($R_s - R_g = 1.5$ m); the initial temperature of the foam is 248 K; there is thermal contact between the foam and the hydrate; the temperature of the outer surface of the storage-shelter (T_{out}) is constant and is 293 and 265 K for summer and winter, respectively.

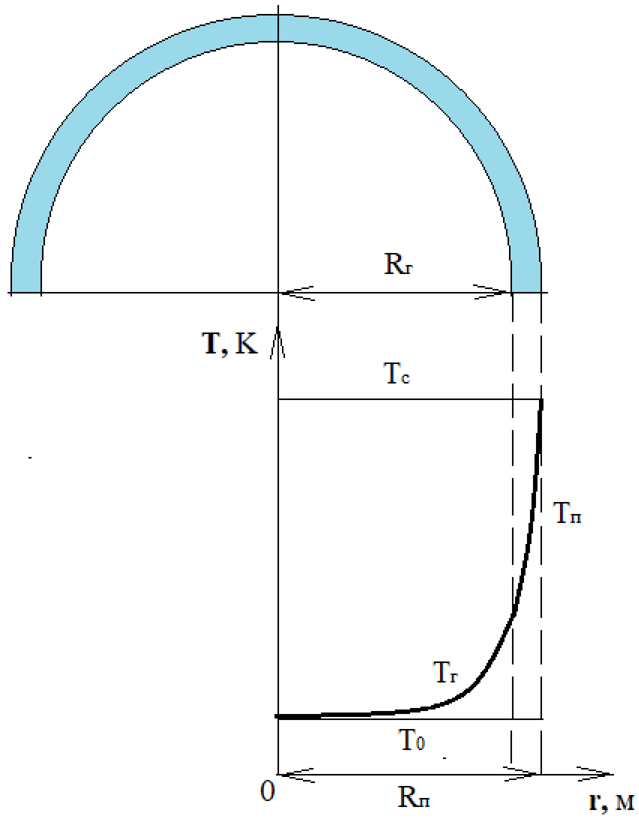

Figure 2. Scheme of the gas hydrate heating process in the storage-shelter.

It is necessary to find the temperature distribution over time and establish the moment when the temperature of the surface of the gas hydrate reaches 258 K (equilibrium temperature).

This process is described by a system of differential equations. The change in gas hydrate temperature is described by the equation:

$$\frac{\partial[rT_g(r,\tau)]}{\partial\tau} = a_g \frac{\partial^2[rT_g(r,\tau)]}{\partial r^2}$$

$$(\tau > 0, 0 < r < R_g)$$

Temperature change in the foam layer as a result of heat exchange with the gas hydrate and the external environment:

$$\frac{\partial[rT_s(r,\tau)]}{\partial\tau} = a_s \frac{\partial^2[rT_s(r,\tau)]}{\partial r^2}, \qquad (\tau > 0, R_g < r < R_s);$$

$$\frac{\partial[rT_s(r,\tau)]}{\partial\tau} + \alpha(T_{out} - T(R,\tau) = 0$$

Initial conditions of the process:

$$T_g(r,0) = T_0; T_s(r,0) = T_0.$$

Boundary conditions of the process:

$$T_g(R_g,\tau) = T_s(R_g,\tau); \lambda_g \frac{\partial T_g(R_g,\tau)}{\partial\tau} = \lambda_s \frac{\partial T_g(R_g,\tau)}{\partial\tau};$$

$$T_s(R_s, \tau) = T_{out}; T_g(0, \tau) \neq \infty.$$

where r – variable (current) value of the radius of the storage base, m; R_g – radius of the base of the storage-shelter located under the gas hydrate embankment, m; R_s – the radius of the base of the storage-shelter, which is located under the gas hydrate mound and the foam layer, m; T_o – storage temperature of gas hydrate, initial temperature of gas hydrate and foam layer, ($T_o =$ 248), K; T_{out} – ambient temperature (293 K in summer, 255 K in winter); T_g – variable over time (current) gas hydrate temperature, K; T_s – variable over time (current) temperature of the foam layer, K; τ – the time of the heating (cooling) process of gas hydrate and foam; λ_g – coefficient of thermal conductivity of gas hydrate, W/(m K);λ_s – coefficient of thermal conductivity of foam, W/(m K); a_g – coefficient of thermal conductivity of gas hydrate, m^2/s; α – heat transfer coefficient, W/K m^2; a_s – coefficient of gas hydrate thermal conductivity, m^2/s.

In order to evaluate the thermal insulation characteristics of the foam and the dynamics of the temperature change of the gas hydrate in the gas-resistant storage-shelter, its computer simulation was carried out (figures 3-6). The above storage calculation parameters were taken as the starting point.

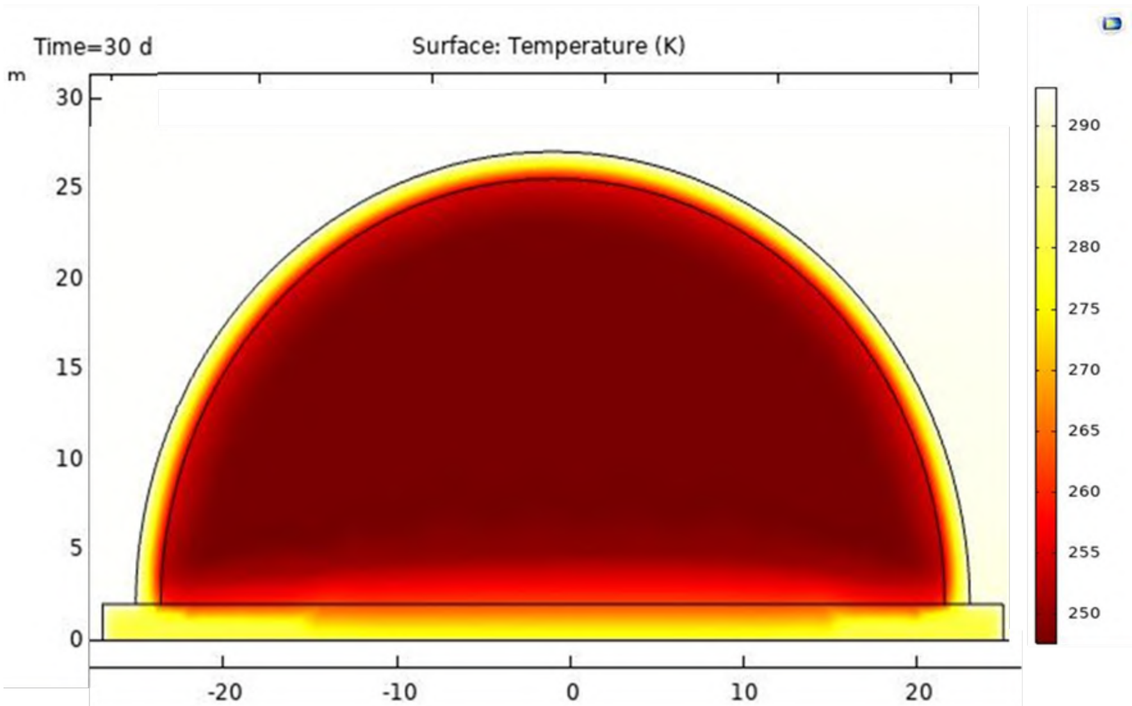

Figure 3. Simulation of heat exchange in summer (external temperature 293 K) of gas-resistant hydrate storage-shelter thermally insulated with liquid foam without additional cooling after 30 days of storage.

Therefore, with an initial temperature of gas hydrates of 248 K, its additional cooling when stored in a storage-shelter facility insulated with foam, even in the summer months, will be necessary after 30 days of storage (to maintain the temperature of the gas hydrate at a level not higher than 258 K).

5. Conclusions

Thus, gas storage in gas hydrate form is proposed to be implemented in improved shell gas-bearing structures. This improvement consists in the use of liquid stable foams as a thermal

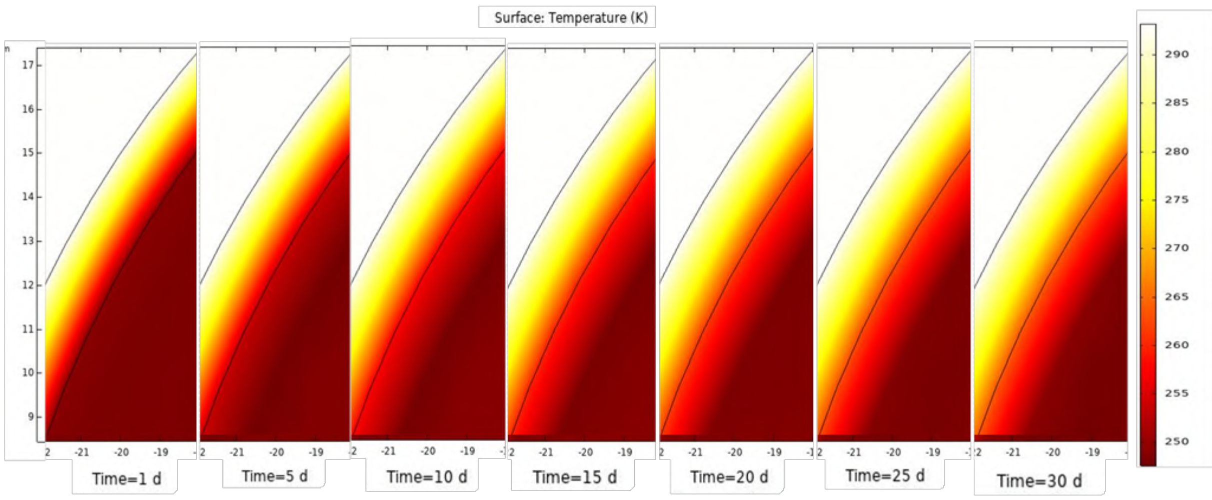

Figure 4. Dynamics of changes in the temperature of the gas hydrate surface and the foam layer in the hydrate storage-shelter in the summer ($T = 293$ K) without additional cooling.

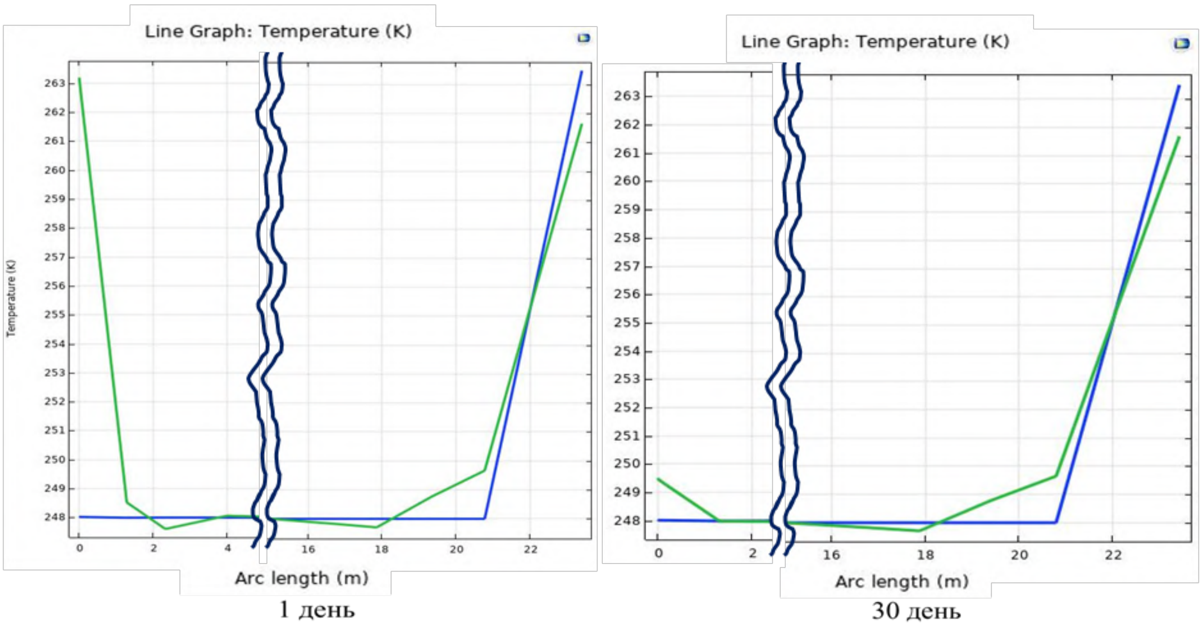

Figure 5. Dynamics of changes in the temperature of the gas hydrate (with an initial temperature of 248 K) from the surface to the center of the sole of the stack in the summer period of storage ($T = 293$ K) without additional cooling, provided that it is thermally insulated with a layer of foam 1.5 m thick: a) at the end of the first days of storage; b) at the end of the thirtieth day of storage.

insulation material. The main design elements of this storage-shelter facility are a frameless gas-resistant shelter in the form of at least two dome-shaped gas-tight soft shells on a thermally insulated base, the space between which is filled with liquid foam. The use of these hydrate storages will significantly increase the efficiency and competitiveness of natural gas storage technology in the form of gas hydrates.

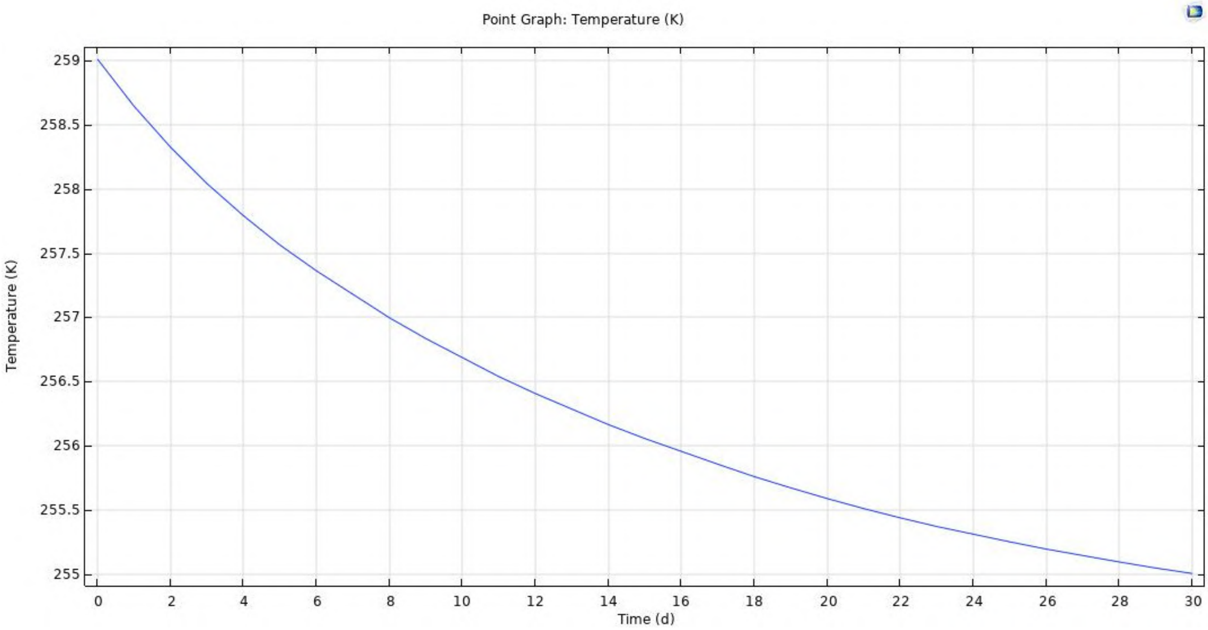

Figure 6. Dynamics of changes in the temperature of the gas hydrate surface (with an initial temperature of 248 K) during thirty days in the summer storage period (T = 293 K) without additional cooling, provided that it is thermally insulated with a layer of foam 1.5 m thick.

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References

[1] Sloan E D 2003 *Nature* **426**(6964) 353–359 ISSN 1476-4687 URL https://doi.org/10.1038/nature02135
[2] Carroll J J 2014 *Natural Gas Hydrate: A Guide for Engineers* 3rd ed (Elsevier Science & Technology Books) URL http://182.72.188.194:8080/jspui/bitstream/123456789/1509/1/Natural%20Gas%20Hydrates%20a%20Guide%20for%20Engineers%20by%20John%20Carroll.pdf
[3] Sloan D, Koh C, Sum A K, Ballard A L, Creek J, Eaton M, Lachance J, Mcmullen N, Palermo T, Shoup G and Talley L 2010 *Natural Gas Hydrates in Flow Assurance* (Gulf Professional Publishing) URL https://doi.org/10.1016/C2009-0-62311-4
[4] Gudmundsson J S, Parlaktuna M and Khokhar A A 1994 *SPE Production & Facilities* **9**(01) 69–73 ISSN 1064-668X URL https://doi.org/10.2118/24924-PA
[5] Gudmundsson J S and Parlaktuna M 1991 Gas-in-ice: Concept evaluation Tech. rep. Department of Petroleum Engineering and Applied Geophysics, Norwegian University of Science and Technology Trondheim
[6] Takeya S, Ebinuma T, Uchida T, Nagao J and Narita H 2002 *Journal of Crystal Growth* **237-239**(1) 379–382 ISSN 0022-0248 The thirteenth international conference on Crystal Growth in conj unction with the eleventh international conference on Vapor Growth and Epitaxy URL https://www.sciencedirect.com/science/article/pii/S0022024801019467
[7] Narayanan S 2019 *Building Materials, Testing and Sustainability* (New Delhi: Oxford University Press)
[8] Pashchenko T M and Svitla Z I 2005 *Budivelne materialoznavstvo* (Kyiv: Technika)
[9] Pedchenko M, Pedchenko L and Pedchenko N 2020 Increase of Thermal Resistance of the Gas-Filled Shell and Pneumatic Building for Use as Natural Gas Storages in Gas-Hydrated Form *Proceedings of the 2nd International Conference on Building Innovations. ICBI 2019. Lecture Notes in Civil Engineering* ed Volodymyr O, Gulchohra M, Svitlana S and Akif G (Cham: Springer Cham) p 701–7087 ISBN 978-3-030-42939-3 URL https://doi.org/10.1007/978-3-030-42939-3_69
[10] Jamil R, Shehzad M A and Mehmood N 2005 *Study and adaptability of pneumatic structures* Thesis for

Bachelor of Engineering (Civil Engineering) Military College of Engineering, Risalpur, National University of Sciences and Technology Risalpur, Rawalpindi, Pakistan URL https://doi.org/10.13140/RG.2.2.25855.61608
[11] Ermolov V V 1980 *Vozdukhoopornie zdanyia y sooruzhenyia* (Moscow: Stroiyzdat)
[12] Orsa Y N 1983 *Osobennosty arkhytekturi pnevmatycheskykh vozdukhoopornikh sooruzhenyi. Pnevmatycheskye stroytelnie konstruktsyy* (Moscow: Stroiyzdat)
[13] Budyko M I 1961 *Soviet Geography* **2**(4) 3–13 URL https://doi.org/10.1080/00385417.1961.10770761
[14] Malyarenko V A, Redko A F, Chaika Y I and Povolochko V B 2001 *Tehnicheskaya teplofizika ograzhdayuschih konstruktsiy i sooruzheniy* (Kharkov: Rubicon)
[15] Ponomarchuk I A and Voloshyn O B 2004 *Ventyliatsiia ta kondytsiiuvannia povitria* (Vinnytsia: VNTU)
[16] Malyarenko V A 2006 *Osnovy teplofizyky budivel i enerhozberezhennia* (Kharkiv: SAGA)

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Biocenotic influence of the great cormorant (*Phalacrocorax carbo* L.) in the Azov-Black sea region of Ukraine

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Biocenotic influence of the great cormorant (*Phalacrocorax carbo* L.) in the Azov-Black sea region of Ukraine

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Abstract. The great cormorant (*Phalacrocorax carbo* L.) is a bird species that, due to the peculiarities of its biology, can significantly affect the natural environment. First of all, due to the fact that the species is an obligate ichthyophage and feeds exclusively on fish (causing, in some places, quite significant damage to both the fishery and the natural fish resources of the seas), a large amount of potassium, nitrogen and phosphorus compounds accumulates in its feces. Because of this, the caustic excrements of cormorants have a detrimental effect on herbaceous and woody vegetation in the colonies of this species, near them, as well as in the resting places of the birds. Considering the fact that the nesting colonies of the great cormorant can be quite numerous, reaching tens of thousands of nests (such as the settlement on the Obytichna spit in the Berdyansk district of the Zaporizhzhia region), the impact is observed to be very significant. At the same time, tree vegetation suffers from mechanical damage during the construction of nests, and trees die after 2-3 years. Another type of influence of cormorants is their interaction with other bird species in nesting areas. The high number of cormorants leads to a reduction in the number of some other bird species, the impoverishment of nesting bird complexes (herons, terns); in the conditions of a shortage of nesting sites on the islands, only (*Larus cachinnans* can nest together with the great cormorant (with its high number). We observed a similar situation in most nesting settlements of the species.

1. Introduction

The scientific literature has accumulated a lot of information about the impact on the environment (including its physico-chemical and biological regimes) of various organisms [1]. The environment-forming activity of birds is most significantly and visibly manifested in the places of their mass gatherings. Large colonies play an important role in soil formation, bringing a large number of organic substances with the products of life (mainly guano). Special ornithogenic soils are formed in places of bird gatherings, in which the concentrations of phosphorus and nitrogen can exceed the corresponding background indicators by two times, and zinc and potassium – by one and a half times. Under the influence of atmospheric precipitation, leaching of easily soluble compounds of phosphorus, nitrates, sulfates and chlorides occurs from the litter.

The participation of birds in the transport of biogenic substances from aquatic to terrestrial ecosystems is indisputable. Japanese scientists analyzed the long-term consequences of the nesting of the great cormorant (*Phalacrocorax carbo*) and its participation in the nitrogen cycle [2]. These birds feed on fish in fresh water bodies, and nests are built on trees in the forest. In nesting places, trees die, and in the territories of former cormorant settlements, the increased content of nitrogen in litter, soil and plants remains for a long time. Similar pictures are observed in many places along the coasts of different seas. Birds' excrements entering the water sometimes affect the dynamics of biogenic substances so significantly that some foreign colleagues began to use a special term – "guanotrophication".

Another important type of impact of the great cormorant is its relationship with other species of birds, especially, the wetland complex birds, which depends, first of all, on the characteristics of the species that nest in mixed settlements with the great cormorant, as well as the specifics of the nesting sites – the type of nest biotope, shortage of suitable nesting area, etc. The impact can be both direct and indirect, and can be both negative and, in some cases, positive. The material presented below is based on the results of own expedition trips and analysis of literary sources [3, 4].

2. Material and methods

Researches of the ecological impact of the great cormorant were conducted in the Azov-Black Sea region of Ukraine in 22 nesting colonies of this species in the period from 2012 to 2021 (figure 1). Most of the expedition work was carried out using the methods of fixed vehicle, boat and pedestrian census. Surveys were made with Etherna binoculars (10x) and Nikon ACULON A211 10x50 and VIXEN Geoma telescope (20-60x80). Mapping of bird gathering places and spatial characteristics of routes were made using a GARMIN GPSMAP 78s navigator. Biotopes and birds were photographed with Canon EOS 450D and Nikon D700 cameras. The photographs were exported to the FastStone Image Viewer programme, which together with the camera software in the Exif metadata mode made it possible to control the geolocation data of the photographs taken, the date and conditions of shooting. Linear dimensions between objects and object heights were measured using a Nicon Forestry 550 laser altimeter. Statistical processing of the obtained data was carried out in Microsoft Excel 2010 and Statistica Release 8 (Basic Statistic module) programmes.

In general, such a phenomenon as the influence of the great cormorant on natural and anthropogenic complexes, in particular, the negative impact on vegetation, other species of colonial wetland birds, pond fish farms, technical structures, etc., is quite well known and repeatedly described in the scientific literature. Also, many different publications and studies are devoted to issues of human influence on the number and distribution of the great cormorant, methods of regulating its number. Therefore, the purpose of this research is only to provide data available in Ukraine on the impact of the cormorant on vegetation, soil and ornithocompexes.

3. Results

The biocenotic significance of great cormorant colonies and their negative impact on vegetation is mentioned in the works of many authors. The forms and scales of this phenomenon depend on the number of cormorants, the method of nesting (tree, shrub or ground colonies), the species diversity of accompanying species, the duration of the impact (intraseasonal and perennial aspects) and other factors.

3.1. Impact on vegetation

3.1.1. Terrestrial colonies. One of the most comprehensive researches in Ukraine on the study of the biocenotic influence of ground colonies of the great cormorant was conducted in 1997-2003 on the Lebedyni islands. They made it possible to conclude that this species has a decisive influence on the composition, structure and distribution of vegetation on the islands. Cormorants are most destructive to vegetation during the period when they are building their nests. Nests are completed and renewed during the entire reproductive period, but their building is especially active during the laying and hatching of eggs. Birds collect nesting material within a radius of

Figure 1. The territory of research in the Azov-Black Sea region of Ukraine in 2012-2021: 1 – the shore of the Dniester estuary, 2 – the Konka River, 3 – Krasnykivs'kyi island, 4 – Ustup channel, 5 – Milkyi estuary, 6 – Kaznacheys'kyi estuary, 7 – Didiv estuary, 8 – Sabets'kyi estuary, 9 – Karzhins'ki islands in the Dzharylhach bay, 10 – Kalanchak islands, 11 – Ustrychni islands near the Hirkyi Kut peninsula (Khorly), 12 – Kytai island, Central Syvash, 13 – Syvashivka islands, 14 – islands of the Koyanly system, 15 – islands of the Maslyna tract, 16 – gas rigs in the Sea of Azov, 17 – tree plantings on the Obytichna spit, 18 – Zigzag island at the bottom of Obytichna spit, 19 – crossings of 330 and 750 kV power transmission lines across the Kakhovka reservoir near the town of Enerhodar, 20 – Ivanivski Kuchuhury archipelago, 21 – Velyki and Mali Kuchuhury archipelago, upper reaches of the Kakhovka reservoir, 22 – o. Dubovyi between o. Khortytsia and Dnieper Hydroelectric Station.).

up to 2 km from the colony. Some birds find the material in the immediate vicinity of the nest, others collect it on neighboring islands and some "steal" it from the nests of other cormorants. The cormorant uses *Artemisia* sp., as well as last year's shoots of *Atriplex tatarica*, *Pontic catrana*, rhizomes and stems of *Phragmites australis*, pulling them out of the soil to build their nests. The influence of the cormorant on vegetation is not limited to nest-building activities, it experiences a depressing effect as a result of trampling by birds, compaction of the soil, as well as "burning" with excrement, since raw bird feces contain up to 16.3% of nitrogen, 15.4% of phosphorus, 8.5 – potassium, 24.0 – calcium and 7.4% manganese. At the locations of the colonies, there is a change in vegetation cover, while in the first year, as a result of strong nitrification of the substrate, species that prefer nitrogen-rich soil prevail. In the following years, even in the absence of birds, communities dominated by spring or winter annuals are observed in the colony for a long time, the vegetation cover is transformed, including the impoverishment of the coenotic and floristic structure of the island complexes. The restoration of communities with the participation of perennials, including *Artemisia* sp., *Crambe pontica* and *Leymus sabulosus*, does not occur in the first 10 years, and during this period, areas with disturbed plant cover in the conditions of the Lebedyni islands are most often washed away as a result of a decrease in the turf of the substrate, an increase in the influence of wind erosion, decrease in wave resistance of accumulative shores.

A similar situation is observed for the islands of Tendra and Yahorlyk bays, where the ground nesting sites of the cormorant very quickly become devoid of any vegetation cover, which is connected both with the direct destruction of the vegetation used for building nests, and with accumulation in the soil out-of-boundary concentrations of phosphorus and nitrogen that enter there from bird feces. At the same time, even after the cessation of the existence of the colony, the restoration of vegetation occurs after at least 2 years. Another negative consequence of the destruction of vegetation at the place of cormorant colonies, if they are located near a water cut, is the acceleration of the erosion process of the coastal edge of the islands and, as a result, a gradual decrease in the area of the islands, including those suitable for nesting.

On Kryva spit, the great cormorant usually occupies nesting sites at the very beginning of the growing season of the main types of plants of the Kryva spit, such as *Leymus sabulosus*, *Melilotus* sp., and *Crambe pontica*. As a result of the impact of cormorant feces, all vegetation in the territory of the colony dies, while in neighboring areas it can reach up to 1 m in height.

3.1.2. Arboreal colonies. The largest colonies of great cormorants located on trees are located on the coast of the Sea of Azov – the Kazantyp Peninsula (Mysove Forestry), Obytichna spit, the Dnipro reservoirs – Kakhovka (Velyki Kuchuhury), Kremenchuk, Kaniv, Kyiv reservoirs, as well as in a number of other places. Everywhere, the negative impact of the nesting of this species, both on herbaceous and tree-shrub vegetation, is noted, which in the case of large colonies acquires a significant scale. The most thorough studies of the influence of cormorant colonies on tree and shrub vegetation were conducted by S. M. Podorozhnyi in June-July 2008 on the islands of Velyki and Mali Kuchuhury, and the previous results were confirmed by our expedition trips in 2012-2017.

They showed that the tree vegetation on the islands is represented by two types of plantings. The first is the most common and is represented by trees located along the coastline of large and small islands that are part of the reserve. *Salix alba* is the dominant species here. *Populus alba* and *P. nigra* were much less common in these stands. The height of the stands of these species is 18-20 m, and the average age is 50-60 years. *Morus nigra*, *Acer negundo*, *Fraxinus excelsior* can be found singly in these plantings. The vast majority of these are low-growing trees of coppice origin. The shrub layer of coastal tree plantings is represented by *Sambucus nigra* and *Amorpha fruticose*.

Coastal plantings suffer the most from the settlements of the great cormorant, as they are chosen by the birds for placing their nests in the first place. Tall *Salix alba* and *Populus* sp. trees with a good view and an uncomplicated approach to the nest are chosen as nesting biotopes. Nests, as a rule, are arranged in the upper and middle parts of the crown of trees at the base or middle part of branches of the second order. The negative impact on the growth and development of trees is primarily associated with the impact of bird feces with a high concentration of nitrogen, phosphorus and potassium on the vegetative organs of plants during the entire nesting period. This leads to the death of leaves and young shoots as a result of burns. In the first year of the appearance of nests on trees, the leaves of the upper and partly the middle part of the crown "burn". As a result, the bark of the skeletal branches in the upper part of the crown peels off and the tree begins to dry out.

The next year, the upper dry parts of the trees, in most cases, are used by the cormorant as a roost, and the nests are moved to the middle part of the crown, where the leaves are still partially preserved. By the end of the growing season, the leaves and one-year shoots of the middle and lower part of the crown "burn", the bark of the perennial shoots peels off, and the tree dries up completely.

In the future, dead trees are used by cormorants as roosts, and nests are moved to nearby living trees. In the absence of trees, cormorants begin to use shrubs (mainly *Sambucus nigra*) with a height of 2.5-4.0 m as nesting biotopes. Much less often, tree forms of trees are used for placing nests – *Acer negundo*, *Morus nigra*, etc. with a similar height. *Amorpha fruticose* and coppice forms of trees die in the first year after placing nests on them. *Sambucus nigra* is more stable and, depending on the intensity of the impact, can vegetate for several seasons, but in the future it also dies.

Monodominant thickets of *Phragmites australis* later form on the site of dead shrubs, which, as a rule, are not used by cormorants as nesting biotopes.

Thus, we can state the fact that the nesting of the great cormorant on the islands of Velyki and Mali Kuchuhury leads to the degradation of coastal tree plantings and their replacement by unproductive monodominant thickets of *Phragmites australis* with low biological diversity. In addition, the degradation of coastal tree plantings is extremely negative, as it can lead to the intensification of coastal erosion processes, which endangers the existence of the islands themselves. Dead trees cannot perform the functions of shore protection and shore fortification. To a much lesser extent, it is performed by shrubs and, even more so, reedy coenoses, which is the last stage of succession.

The second type of tree plantations is found in the interior of large islands with a more elevated topography. They are limited to inter-arena depressions and hollows with close groundwater, forming so-called “groves” or “kolkas”. The structure of tree and shrub plantings here depends on the degree of moisture in the central part. Kolka plantings are used by the great cormorant as a nesting biotope only when there is a shortage of them in the composition of coastal tree plantings. Cormorants choose tall *Salix* sp. and *Populus* sp. trees in the central part for nesting. In dry depressions, *Betula* sp. and *Populus* sp. are used to build nests.

The activity of cormorants directly and indirectly affects the natural complex of the Obytichna spit. Arboreal colonies of the great cormorant are a relatively new phenomenon here, and very detrimental to artificial forest plantings on sandy soils. The high content of nitrogen, phosphorus and other chemical elements in bird feces, and their accumulation during the nesting period (from the end of February to the middle of June) leads to the death of almost the entire grass cover. Instead of natural associations, for the 2nd-5th year, ornithogenic ones are formed, represented by lush thickets of weeds (*Chenopodium* sp., *Melilotus* sp. etc.). In some areas, vegetation disappears almost completely. According to our observations, restoration of herbaceous vegetation at the site of the colony occurs in the second or third year when the impact is stopped.

Similar processes take place in other colonial settlements of the species, both in Ukraine and abroad.

3.2. Impact on soil cover

Waterbirds, such as the cormorant, are very important intermediate links in some food chains and a factor that facilitates the dislocation of matter between aquatic and terrestrial ecosystems. From one perspective, cormorants exclude biogenic elements (along with fish) from aquatic ecosystems. Although cormorants hunt at a fairly large distance from colonies, within a radius of up to 30 km, they leave feces in a relatively small area below the colony and near the lake shore. Nesting colonies of fish-eating birds affect the habitats and phytocenoses they occupy in different ways. During the breeding season, cormorants transfer large amounts of biomass and chemicals from the aquatic environment to colonies located on land. The consequence of the introduction of allochthonous matter into the terrestrial ecosystem can be significant enrichment of soil and plants with nitrogen (N), phosphorus (P) and potassium (K). Elevated concentrations of N and P within the colony may accumulate in the soil and be transported with groundwater or surface runoff to lakes. The range and rate of changes that occur depend mainly on the species of nesting birds, the density and the age of the colony. In addition, cormorants break branches during nest construction, resulting in defoliation of the soil under trees. In areas with high bird density, feces cover herbaceous vegetation, limiting photosynthesis and ultimately leading to plant extinction.

It should be noted that the initial impact of introduced organic elements in the colony leads to an increase in the biological diversity of plants. An assessment of changes in the amount of nutrients accumulated in soils and groundwater, and changes in the floral composition of the forest phytocenosis, which occurred 5 years after the cormorants left the colony, was carried out. The colony, located on a small (0.6 ha) island in Lake Wielkie, has been inhabited by cormorants since the 1980s. The maximum indicated number was about 200 nesting pairs. Research on the impact of the former nest colony on the ecosystem of the island and the surrounding lake was conducted in 2009-2010. Compared to the control station, significantly increased concentrations of nitrogen, phosphorus and potassium were found in the soil under the colony. The highest concentrations of nitrogen were noted in the surface organic layer of soils under the colony. Organic nitrogen dominated among different nitrogen forms (ammonium nitrogen and nitrates were present in the surface layer in much lower concentrations – approximately 200 mg $N\text{-}NH_4$ kg^{-1} and 40 mg $N\text{-}NO_3$ kg^{-1}, respectively). Regarding phosphorus, the highest concentration was found in the deeper soil layers below the colony. Statistically, the concentrations of chemical elements in the soil profiles located in the areas under the colony were significantly different from the concentrations at the control stations (ANOVA, $p < 0.005$). Moreover, an increased concentration of nutrients and other chemical elements in comparison with the control stations was found in the groundwater under the cormorant colony. The underground water under the colony contained a significantly larger amount of dissolved mineral salts – the electrolytic conductivity was almost 5 times higher than at the control station. In addition, nitrogen and phosphorus concentrations in groundwater were significantly higher. Comparing the abandoned colony with the control station (an island not occupied by cormorants), it was found that the floristic composition of the phytocenosis of the forest is very low. All trees were destroyed by birds, and the island is covered with nitrophilous *Sambucus nigra*. A dense canopy of *Sambucus nigra* trees created shading, so there are no grasses at all. Only in the transition zone between the land (colony) and the lake ecosystem are some herbaceous plants: *Urtica dioica* and *Phragmites australis*. Plant biodiversity noted on the control island is much higher – 6 species of trees and shrubs and 17 species of herbaceous plants.

Marion et al [5] found large differences in nutrient content between soil within bird colonies and areas without them at Lake Grand Lieu (western France) (8 times more nitrogen and 42 times more phosphorus at nesting colony sites). In Poland, despite a small proportion of nutrients introduced by cormorants directly into the Dobczyce Reservoir, a high concentration of nutrients was found in the soil and sediments within the cormorant colony [6]. In another research, soil from an island occupied by birds was characterized by higher concentrations of NO_3^-, NH_4^+, and total N than soil from an island without colonies [7]. Similarly, soil samples in the area of cormorant colonies had many times higher content of all investigated chemical elements compared to control samples. The amount of NO_3^- in the soil of the great cormorant colony in Kąty Rybackie (northern Poland) was 94-216 times higher in the surface layer and 7-12 times higher in the deeper layer than in the control plots. The high concentration of NO_3^- showed that nitrification is a very important and intensive process in soil exposed to bird colonies [8].

3.3. Impact on ornithocompexes
The relationship of the great cormorant with other waterbirds depends, first of all, on the characteristics of the species that nest in mixed settlements with the great cormorant, as well as the specifics of the nesting sites – the type of nesting biotope, the lack of suitable nesting areas, etc. The impact can be both direct and indirect, and can be both negative and, in some cases, positive.

The analysis of the available data on the 56 species associated with the great cormorant in 20 mixed settlements (table 1) allows us to state that, depending on the colony, the composition of the avifauna complex can vary greatly, ranging from 3 to 20 species.

Table 1: Associated species in great cormorant colonies in the Azov-Black Sea region of Ukraine (Nesting colonies, [9] and our data).

№	Species	Kruhly island, Yahorlyk Bay	Kins'ki islands; Yahorlyk Bay	islands of the Gulf of Tendra	Karzhynsky islands	Kalanchak islands	Ustrychni islands	Tanin island	Lebedyni islands	Kytai island	Syvashivka islands	Henichesk islands	Semenivskyi Kut	Chonhar islands	Koyanly islands	lake Achi	Pidkova and Dovhyi islands in the Molochny estuary	islands of the Obytichna Bay	Obytichna spit	Kryva spit	Velyki Kuchuhury islands
1	*Podiceps cristatus*								+								+	+			+
2	*Pelecanus onocrotalus*			+																	
3	*Pelecanus crispus*																			+	
4	*Phalacrocorax carbo*	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
5	*Ixobrychus minutus*																				+
6	*Nycticorax nycticorax*																				+
7	*Ardeola ralloides*								+												+
8	*Egretta alba*				+	+			+									+			+
9	*Egretta garzetta*		+	+	+	+	+		+									+	+		+
10	*Ardea cinerea*				+	+	+		+									+	+		+
11	*Ardea purpurea*					+															
12	*Platalea leucorodia*										+										
13	*Plegadis falcinellus*						+		+												
14	*Tadorna tadorna*								+	+											
15	*Anas platyrhynchos*				+	+			+			+			+		+				+
16	*Anas strepera*					+			+			+			+		+				+
17	*Anas querquedula*																+				
18	*Netta rufina*								+												
19	*Aythya ferina*								+												
20	*Somateria mollissima*	+		+		+															
21	*Mergus serrator*				+	+	+		+												
22	*Circus aeruginosus*					+															
23	*Falco vespertinus*																		+		
24	*Falco tinnunculus*																		+		
25	*Anthropoides virgo*										+										
26	*Rallus aquaticus*																+				
27	*Gallinula chloropus*								+								+				+
28	*Fulica atra*								+								+				+
29	*Charadrius dubius*						+					+	+	+	+						
30	*Charadrius alexandrinus*					+	+					+	+	+	+		+				
31	*Recurvirostra avosetta*										+	+	+		+		+				
32	*Haematopus ostralegus*		+		+	+	+	+	+	+	+	+	+	+	+		+				

Continued on next page

Table 1 – continued from previous page

№	Species	Kruhly island, Yahorlyk Bay	Kins'ki islands; Yahorlyk Bay	islands of the Gulf of Tendra	Karzhynsky islands	Kalanchak islands	Ustrychni islands	Tanin island	Lebedyni islands	Kytai island	Syvashivka islands	Henichesk islands	Semenivskyi Kut	Chonhar islands	Koyanly islands	lake Achi	Pidkova and Dovhyi islands in the Molochny estuary	islands of the Obytichna Bay	Obytichna spit	Kryva spit	Velyki Kuchuhury islands
33	*Tringa totanus*				+	+	+	+				+	+		+		+				
34	*Larus ichthyaetus*		+	+					+	+	+			+	+					+	
35	*Larus melanocephalus*			+		+	+	+			+	+			+	+		+			
36	*Larus genei*					+						+			+	+		+			
37	*Larus cachinnans*	+	+	+	+	+	+		+	+	+		+	+	+	+	+	+		+	+
38	*Gelochelidon nilotica*						+	+			+				+	+	+				
39	*Hydroprogne caspia*			+					+	+				+							
40	*Thalasseus sandvicensis*			+			+	+				+	+		+		+	+			
41	*Sterna hirundo*		+	+		+	+	+			+	+		+	+	+	+	+			
42	*Sterna albifrons*						+	+				+		+	+		+	+			
43	*Alauda arvensis*											+			+						
44	*Motacilla feldegg*											+			+						
45	*Lanius collurio*																		+		
46	*Lanius minor*																		+		
47	*Pica pica*																+		+		
48	*Corvus cornix*																		+		+
49	*Corvus corax*																				+
50	*Muscicapa striata*																		+		
51	*Oenanthe oenanthe*																		+		
52	*Acrocephalus agricola*				+	+	+					+			+		+				
53	*Acrocephalus arundinaceus*											+									+
54	*Emberiza calandra*																		+		
55	*Emberiza citrinella*																		+		
56	*Emberiza schoeniclus*																+				
	Total	3	6	10	10	18	16	8	19	6	10	17	8	9	19	6	20	11	13	4	16

On the Obytichna spit, the growth of the great cormorant population affects the species composition and the number of other satellite birds, although this is clearly manifested only at high values. The limited nesting of great cormorants on 1-2 islands (until 2002) did not affect other nesting bird species, but after the spread of cormorants on 5 islands (2007-2008), significant changes in bird communities became noticeable. The number of species of the avifauna complexes of the Obytichna spit is inversely proportional to the increase in the number of great cormorants. Until 2002, 8-11 species of waterbirds nested here, and in 2007-2008 – only three species. Since 1993, the cormorant has gradually displaced such species as *Egretta alba*, *Egretta garzetta* and *Ardea cinerea*, as well as *Sterna hirundo* and *Sterna albifrons* from the nesting sites. In conditions of scarcity of nesting sites on the islands, only *Larus cachinnans* can nest together with the great cormorant (with its high number). Experiencing territorial competition, he nevertheless takes advantage of joint nesting by eating clutches, cormorant nestlings and collecting food scraps in his colonies.

After the cormorant changed its nesting strategy from terrestrial to arboreal, predation by gulls became even more active. Research conducted during 2015-2021 showed that the first gulls appear in the colony even before sunrise, at 4 o'clock in the morning. After 1.5-2 hours, massive wave-like raids of gulls begin with a frequency of about once an hour. They show the following tactics: while one part of the birds circles over the nests, scaring the cormorants, the other destroys the nests. At the same time, cormorants are reluctant to defend their nests, in most cases they simply fly away or sit on nearby trees.

The intensive increase in the number of cormorants on the spit provides, in addition to Larus cachinnans, a number of other species, in particular, *Pica pica* and *Corvus cornix*, as a food base. Pica pica on the islands steal eggs from terrestrial colonies of cormorants ($n = 12$), *Larus cachinnans* ($n = 3$), Sterna hirundo, Talasseus sandvicensis ($n = 32$), and in reeds – eggs from nests of herons (*Ardea cinerea*, *Egretta alba*, *E. garzetta*) ($n = 5$), warblers (*Acrocephalus arundinaceus*, *A. scirpaceus*) ($n = 3$), small nestlings of great cormorants and herons are occasionally dragged ($n = 7$). Therefore, in the conditions of the spit, *Pica pica* have developed and maintain new specific biocenotic relationships. During the nesting period, she actively gathers food in the nearest colonies of great cormorants, gulls, terns and herons on sea outcrops along the edge of the water, makes significant flights, up to 500-2000 m from the nest outside the nesting territories (data from route records and visual observations).

Corvus cornix is also an active predator of cormorant eggs and young nestlings. This, possibly unintentional, "cooperation" between *Corvus cornix* and *Larus cachinnans* has often been observed: when gulls raid the colony, scaring the cormorants and forcing them to leave their nests, the nests are simultaneously "visited" by crows, which take out eggs and nestlings. The increase in the number of *Corvus cornix* on the Obytichna spit is directly correlated with the increase in the number of cormorant colonies observed in recent years. To a lesser extent, similar behavior is characteristic of *Corvus cornix*, for example, on the Velyki and Mali Kuchuhury islands, where it is a companion species for all cormorant colonies known here.

We observe a different situation in Syvash. The competition of species for nesting territories determines the conditions of their existence, which we traced on the islands of Central and Eastern Syvash for the great cormorant and *Larus cachinnans*, as the most massive colonial species. Research (retrospective analysis and own data) covers the period from the late 1990s to 2021, when the location, number and species composition of colonial bird settlements were characterized by the method of absolute records.

The main perennial nesting sites of this pair of species have been identified. In Central Syvash, this is Kytai island, and in the East – the islands of Chonhar, Koyanly, Arabat spit, Soleprom and Polyhonna spit. The analysis of the dynamics of the number of species showed the relationship of these areas, expressed in the redistribution of colonies, in which the increase in the number in Eastern Syvash led to its decrease in Central and vice versa. Territorial relations between birds nesting on the Kytai island, are determined by the limited capacity of nesting biotopes, and in the pair "great cormorant – *Larus cachinnans* there is a noticeable inverse correlation ($r = -0.54$), which confirms the territorial competition of these species. At the same time, in relation to Larus ichthyaetus, which also nests on the Kytai island, such competition is not observed.

The great cormorant forms 5 sub-colonies on the island among the associations of *Suaeda salsa* and *Halocnemum strobilaceum*. *Larus cachinnans* also forms 5 sub-colonies in the areas devoid of vegetation, as well as among *Suaeda salsa* and *Ajuga chia*. *Larus ichthyaetus* forms 2 sub-colonies among the associations of Hordeum murinum and *Cerastium holosteoides* with interspersed *Matricaria perforate*. At the same time, 1 subcolony of *Larus cachinnans* and 2 subcolonies of the cormorant were located in the immediate vicinity of the subcolony of *Larus ichthyaetus*, among the areas occupied by *Hordeum murinum* and *Cerastium holosteoides*. Due to the fact that neither *Larus cachinnans* nor the cormorant occupies the nesting stations of *Larus ichthyaetus*, but its number is decreasing, it can be assumed that there is some reduction in the areas occupied by *Hordeum murinum* and *Cerastium holosteoides* by the cormorant and *Larus cachinnans*, which start nesting before *Larus ichthyaetus*. The conducted studies prove this: these types of plants are subject to intense trampling and the influence of guano, which leads to a reduction in areas.

On the Chonhar islands, with a noticeable increase in the number of great cormorants with a maximum in 2012 (2.500 nests), there was no noticeable decrease in the number of subdominant species, among which *Larus cachinnans* is traditionally present ($r = -0.31$). The maximum number of colonial birds on the Koyanly islands is about 17.000 nests, with smaller numbers there is no territorial competition. A regularity was revealed, in which the increase in the number of cormorant species not only does not lead to a decrease in its number, but also significantly correlates with it ($r = 0.57$). A similar picture is observed on the Polyhonna spit. On the islands of Soleprom, a significant decrease in the number of associated species has been observed over the past 15 years due to joint territorial pressure from *Larus cachinnans* and the great cormorant. The cormorant occupies large areas, and *Larus cachinnans* acts as an active predator in relation to other species. Thus, between the great cormorant and *Larus cachinnans*, with a shortage of suitable nesting areas, the competition is fully manifested in Central Syvash. To a lesser extent, competition exists on the islands of Eastern Syvash, where situations where these species did not compete were also observed. Rarer and more interesting were the facts of the joint influence of great cormorants and *Larus cachinnans* on the species accompanying them in the colony.

On the islands of Tendra and Yahorlyk bays, according to the nature of the impact of the great cormorant on the most massive species of the island bird complex, the latter can be divided into two groups: 1 – species on which the great cormorant has a negative impact to varying degrees; 2 – species on which the nesting of the great cormorant has a positive effect. First of all, it should be pointed out that the great cormorant is a strong territorial competitor and the places occupied by the colonies of this species, as well as the areas adjacent to them, become inaccessible for nesting of most of the traditional for the islands' colonial *Charadriiformes* species. In addition, great cormorant nesting sites attract many *Larus cachinnans* to the island, whose predation usually makes nesting on the same island almost impossible for other species of gulls and terns, with the exception of *Larus ichthyaetus* and *Sterna hirundo*. Also, the cormorant's ground nesting places on the islands very quickly become devoid of vegetation. Destruction of vegetation makes areas where cormorants' nest unsuitable for nesting ducks. The great cormorant has a definite positive effect on *Pelecanus onocrotalus*. This species is the center of social attraction for the pelican. Other researchers believe that the nesting colonies of the great cormorant for *Pelecanus onocrotalus* are a marker of the security of the nesting territory. In any case, the presence of nesting colonies of the great cormorant turns out to be an important factor in the restoration and further preservation of the nesting settlement of *Pelecanus onocrotalus* in the Black Sea Biosphere Reserve.

Another species on which the great cormorant has a positive effect on the islands of Tendra and Yahorlyk bays is *Larus cachinnans*. And although, at the first stages of the formation of a nesting settlement on the Kins'ki islands, the great cormorant displaced the gulls from their traditional nesting biotopes in the lower part of the island, where a rather significant death of its nestlings due to rushes was noted, in the future the joint the nesting of these two species turned out to be very beneficial for *Larus cachinnans*. Colonies of great cormorants are a very rich source of food for gulls, which they obtain here both by kleptoparasitism (passive and active) and by predation on eggs and nestlings. It should also be mentioned that some species can use old abandoned colonies of the great cormorant. *Pica pica* and *Somateria mollissima* can nest in the nests of old colonies, and within the abandoned colonies themselves, where the vegetation has not yet had time to recover, sometimes nesting *Thalasseus sandvicensis* and *Sterna hirundo*. According to the above-mentioned authors, in the conditions of low-lying islands, often flooded during rains and driving winds, such a strategy can increase the survival of these species. However, the scale of such a positive effect is extremely insignificant and is completely neutralized by the whole set of negative effects of the great cormorant on the valuable components of the island avifauna complexes of the Tendra and Yahorlyk bays.

4. Conclusion

An analysis of both published and original information concerning the great cormorant in the region allows us to draw the following conclusions:

1. The activity of cormorants affects various components of the natural complexes of the Azov-Black Sea region of Ukraine. Since the great cormorant is an obligate ichthyophage, it exerts a certain influence on the fish productivity of the coastal zones of the Azov and Black seas; fish resources experience a heavy load from the species, especially during the feeding of nestlings.
2. Its impact on herbaceous vegetation is manifested both in a change in the species composition of phytocenoses and in the subsequent disappearance of vegetation in certain areas. Tree vegetation is also negatively affected – mechanical damage to trees by birds when collecting branches for nests, their destruction under the weight of nests, drying of trees due to the effect of large doses of nitrogen and phosphorus compounds from birds' excrements. And in the case of a large area and number of cormorant colonies, the drying of trees occurs on large areas, which can reach tens of hectares, which undoubtedly causes damage to forestry.
3. The high number of cormorants leads to a reduction in the number of some other species of birds, impoverishment of nesting bird complexes (herons, terns); in the conditions of a shortage of nesting sites on the islands, only *Larus cachinnans* can nest together with the great cormorant (with its high number).

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References

[1] Jones C G, Lawton J H and Shachak M 1994 *Oikos* **69**(3) 373–386 URL https://doi.org/10.2307/3545850
[2] Kameda K, Koba K, Hobara S, Osono T and Terai M 2006 *Hydrobiologia* **567**(1) 69–86 URL https://doi.org/10.1007/s10750-006-0052-0
[3] Mukherjee A and Borad C K 2001 *Hydrobiologia* **464**(1) 201–205 URL https://doi.org/10.1023/A:1013966021208
[4] Mulder C P and Keall S N 2001 *Oecologia* **127**(3) 350–360 URL https://doi.org/10.1007/s004420000600
[5] Marion L, Clergeau P, Brient L and Bertru G 1994 *Hydrobiologia* **279–280**(1) 133–147 URL https://doi.org/10.1007/BF00027848
[6] Gwiazda R, Jarocha K and Szarek-Gwiazda E 2010 *Biologia* **65**(4) 742–748 URL https://doi.org/10.2478/s11756-010-0072-0
[7] Wait D, Aubrey D and Anderson W 2005 *Journal of Arid Environments* **60**(4) 681–695 URL https://doi.org/10.1016/j.jaridenv.2004.07.001
[8] Otero X L, De La Peña-Lastra S, Pérez-Alberti A, Ferreira T O and Huerta-Diaz M A 2018 *Nature Communications* **9**(1) 246 URL https://doi.org/10.1038/s41467-017-02446-8
[9] Bagrikova N A and Kostin S Y 2005 *Branta: Transactions of the Azov-Black Sea Ornithological Station* **8** 27–42 URL https://branta.org.ua/en/branta-issues/branta-8/8-03.html

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Accumulation of endocrine-disrupting compounds (EDCs) in Procambarus Virginalis tissue in Dnipro river: ecological and hygienic aspects

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Accumulation of endocrine-disrupting compounds (EDCs) in Procambarus Virginalis tissue in Dnipro river: ecological and hygienic aspects

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Abstract. At present among environmental toxicants, endocrine-disrupting compounds (EDCs) gained the widest distribution due to their presence in chemicals in consumer products and food contact materials, pharmaceuticals, personal hygiene products, and as mycotoxins and phytoestrogens. They are used in animal husbandry as growth promoters and in crop production as pesticides and herbicides. EDCs pollution of water sources is becoming alarming due to the imperfection and difficulty of removing pollutants using traditional water and wastewater treatment processes. Given the EDS activity and genotoxicity, the discharge of these effluents may realize a high risk to aquatic organisms in the receiving environment. Natural and synthetic estrogens are among the most potent endocrine-disrupting compounds found in urban wastewater. The purpose of this work was to determine the concentration of hormones, namely estradiol and cortisol, in Procambarus virginalis hydrobionts of different ages from the Dnipro River in the city of Dnipro. In the presented work, based on a review of modern scientific sources and the results of our own research, emphasis is placed on the need to monitor the accumulation of hormone-like compounds in the tissues of aquatic organisms, namely crustaceans as markers of pollution of aquatic ecosystems by EDCs. The influence of substances destroying the endocrine system is especially dangerous during critical periods of the body's development. In ecological conclusion, EDC accumulation in hydrobiont's species may have a negative impact on species conservation. In hygienic aspect, these substances can affect humans through the food chain as consumers of fish products and seafood contaminated with such toxicants.

1. Introduction

Ecosystem pollution is a serious problem worldwide. Aquatic ecosystems are extremely important for biota, fauna, flora, and humans. In recent decades, there has been a worldwide concern for the environment due to the difficulty of removing pollutants through traditional water and wastewater treatment processes. Among environmental toxicants, endocrine-disrupting compounds (EDCs) encompass nearly 800 different chemicals, including both natural and synthetic compounds, including pesticides, chemicals in consumer products and food contact materials, pharmaceuticals, and personal hygiene products. They alter the activation, synthesis, secretion, and binding of endogenous physiological hormones, thereby influencing several hormonal and metabolic processes. More specifically, they work by mimicking hormones, binding to their receptors and promoting inappropriate responses at inappropriate times or directly blocking their effects [1, 2]. Their progressive exponential occupation and, as a result, waste determine their diffusion and accumulation in the environment. Some EDCs persist in the environment for long periods of time, even after their ban (as an example, the pesticide DDT), due to their insolubility, lipophilicity, and high resistance to degradation [3]. A large number of pollutants that can have an endocrine effect are present in the water environment both individually (in different concentrations) and in complex mixtures [4, 5].

The main source of water pollution is wastewater from various industries. Hormonal activity and genotoxicity of various effluents from textile, paint, electronic and electroplating plants, pulp and paper mills, chemical plants, and municipal sewage treatment plants were evaluated. The results showed the presence of EDS in most industrial effluents. The importance of the city as a huge source of pollution was also confirmed [6]. Municipal sewage, the pharmaceutical industry and hospitals are the biggest sources of steroid estrogens too. Municipal landfills are also sources of organic pollution and may contain leachates with significant amounts of dissolved organic matter, which is partly composed of steroid hormones and other pollutants. In addition to urban pollution, some treated industrial wastewater from processing plants contained phytoestrogens. The filtrate is able to penetrate into groundwater.

Existing wastewater treatment technologies do not fully address the growing water pollution situation from wastewater discharges, especially with the increased use of personal care products and pharmaceuticals in private households and the healthcare sector. The urgency of solving the problem of organic pollutants is taken into account in Directive 2013/39 / EU. In addition, Decision 2015/495 of March 20, 2015 defined a list of 10 pollutants. This list includes several chemicals, including the pain reliever diclofenac and the hormones $17beta$-estradiol and $17alfa$-ethinylestradiol. In addition, it is necessary to take into account the formation and transformation of by-products. Unfortunately, most methods currently in use are unable to completely remove such critical compounds [7].

Endocrine-disrupting chemicals have been found in aquatic environments around the world. Given the EDS activity and genotoxicity, the discharge of these effluents may realize a high risk to aquatic organisms in the receiving environment. Aquatic organisms are particularly affected by anthropogenic pollutants, the effects of which can last a lifetime and are mediated through several pathways, including through the skin and gills, or through feeding on contaminated sediments and bioaccumulation. Aquatic pollutants can compromise reproduction, development, immune response, and other physiological processes that can ultimately affect aquaculture survival. In addition to the direct impact of water pollutants on the population of aquatic organisms that are included in the food chain when used by humans and wildlife, they realize a risk to human health and negatively affect the economics of fisheries and aquaculture [8].

Crustaceans are among the most ecologically significant species in aquatic ecosystems and food webs, playing a crucial role in aquatic ecosystems in transporting food web energy. In addition, these species play an important role as bioindicators in toxicological studies of water pollution. Metabolism of many xenobiotics occurs more slowly in invertebrates than in fish, and therefore invertebrates retain higher levels of contaminants. Therefore, EDS, accumulating in organisms, are a danger to the entire ecosystem through the food web [9].

Bisphenol A (BPA), phthalates (DEHP), polyvinyl chloride (PVC), pesticides, herbicides, and organotin compounds show estrogenic activity. Estrogenic disruption of tissue mineralization in aquatic organisms can have a wide range of consequences, such as increased skeletal abnormalities, altered bone density and mineral homeostasis, which can affect swimming and prey capture and predator avoidance. In addition, a violation of homeostasis can affect the reproduction of wild and cultivated species in aquaculture [10].

Along with estrogens, such a hormone as cortisol, which is a key mediator of the hypothalamicpituitary-adrenal response to stress, has a significant impact on living organisms. While acute changes in its circulating levels are necessary to maintain homeostasis under dynamic environments, its chronic elevation can affect immunity, behavior, and reproduction [10].

The marbled crayfish Procambarus virginalis belongs to freshwater crayfish species. P. virginalis is a popular pet species in Europe and North America. P. virginalis is an invasive species in the Dnipro River in Ukraine. Now the species has been introduced into the natural ecosystems of the Dnipro near the city of Dnipro. Through the parthenogenetic method of reproduction and polytrophic omnivorousness, P. virginalis can withstand low winter temperatures in the European temperate zone.

Studies indicate the need for monitoring to assess certain classes of pollutants, such as EDS, which are known to realize serious toxicological hazards to aquatic biota at low concentrations [4].

The purpose of this work was to determine the concentration of hormones, namely estradiol and cortisol, in Procambarus virginalis of different ages as hydrobiont from the Dnipro River in the city of Dnipro.

2. Methodology

The concentration of estradiol and cortisol was determined by the ELISA method on the Stat Fax 303 plus enzyme immunoassay (Awareness Technology, USA) using standard reagents "EstradiolIFA", "CortisolIFA" (HEMA LLC, Ukraine) according to the instructions for the reagent set. Estradiol level was determined in caviar, embryos, young crustacean carcasses samples of Procambarus virginalis, and the muscles of one-month-old (young) crustaceans, five-month-old (mature) and year-old (older) ones. Cortisol level was fixed in gills and muscles of different age crustaceans, roe, embryos and juveniles of marbled crayfish.

The statistical analysis was performed using the program Statistic 6.0 for Windows. The statistical significance was considered at $p<0.05$. [11, 12].

3. Results and discussion

Endocrine control of homeostasis results from the ability of neurons to integrate diverse sensory and hormonal inputs to coordinate autonomic, behavioral, and endocrine responses in their key regulatory centers responsible for the cascade of hormonal events required to modulate critical body functions such as metabolism, reproduction, growth, water balance etc. [13]. Originally, EDCs were thought to exert their effects primarily through nuclear hormone receptors, i.e. estrogen, androgen, progesterone, thyroid, and retinoid receptors. Further studies have highlighted that they also act through non-nuclear receptors for steroid hormones (e.g., membrane estrogen receptors); non-steroidal receptors (for example, serotonin, norepinephrine, or dopamine receptors); orphan receptors (for example, aryl hydrocarbon receptors); enzymatic pathways involved in steroid biosynthesis and/or metabolism, as well as numerous other mechanisms that overlap with the endocrine and reproductive systems. Some EDCs have a genotoxic effect, causing deoxyguanosine hydroxylation and/or DNA strand breaks (both single and double), thereby promoting the malignant transformation of affected cells. Numerous endogenous and exogenous factors, such as environmental pollution and diet lead to the deterioration of the reproductive health of individuals of all links of the food chain [3, 14, 15].

It is known that reproductive processes in crustaceans are controlled by the endocrine system. These hormones play a significant role in normal growth and development. Water pollutants can impair reproduction, development, immune response, and other physiological processes, which can ultimately affect the survival of aquatic organisms. 17beta-estradiol (E2) is important for the development of crustacean ovaries. Ovaries, hepatopancreas, hemolymph, and nervous tissues have been shown to be target organs for compounds with estrogenic activity in crustaceans, and concentrations of 17beta-estradiol in various tissues are closely related to vitellogenesis in the ovary and hepatopancreas during ovarian development [16, 17].

Epigenetic programming established during development can be altered by exposure to EDCs during sensitive periods such as the preovulatory and ovulatory phases and cause immediate adverse outcomes. In addition, changes in methylation profiles and acetylation landscapes that occur during these periods may predispose to the development of pathologies that occur later in childhood or adulthood and, more dramatically, may even be transmitted from generation to generation [3].

According to the results of our research, the average level of estradiol in caviar samples of Procambarus virginalis was 2107 ng/g fresh weight, embryos – 2876 ng/g, and young crustacean carcasses – 4924 ng/g.

In the muscles of one-month-old (young) crustaceans, the average level of estradiol was 4634 ng/g of fresh weight, five-month-old (mature) – 4854 ng/g, year-old (older) – 4877 ng/g of fresh weight. These results highlight the ubiquitous bioaccumulation of estrogens in aquatic invertebrates depending on the duration of exposure.

The distribution of estradiol in the muscles of Procambarus virginalis can directly and effectively reflect the effects of EDC. Xenoestrogens can act on several mechanisms simultaneously. Estrogenic xenobiotics also disrupt the physiology of aquatic organisms, biochemical processes as triggers of oxidative stress, can affect their reproductive development, cause transcriptional effects, and they are also quite powerful initiators of signal cascades from membranes. Transfer of estradiol from the digestive system of Procambarus virginalis to muscle may pose a potential risk to aquaculture, wildlife and human health associated with the consumption of aquatic meat. Finally, they contribute to the general accumulation of estrogen in the environment.

It has been shown that herbicides, namely atrazine, which is commonly found in water bodies, affect the reproductive process of the corresponding fauna, acting as an endocrine disruptor. In this sense, it is suspected that this herbicide affects the secretion of some neurohormones involved in gonadal growth and also changes the circulating levels of steroid hormones that promote the synthesis of vitellogenin for ovarian growth. In addition, atrazine-induced sexual differentiation of young crayfish towards a greater proportion of females reduced offspring production, as well as several embryonic abnormalities, and had a genotoxic effect on crayfish. Finally, some metabolic imbalances, such as reduced energy stores, are observed in some species along with oxidative stress and histopathological effects. as well as suppression of the cortisol response [18].

Cortisol functions as both a glucocorticoid and a mineralocorticoid, which is explained by the unusual structure of its receptors, particularly in fish. This hormone affects the metabolism of carbohydrates, proteins and fats, and also performs important functions related to osmoregulation, growth and reproduction. It is commonly called the hyperglycemic hormone, which ensures the presence of a certain level of glucose in the blood. In aquatic animals, it is an important component in the stress response. Thanks to the timely correction of metabolic processes by this hormone, there is an even distribution of energy resources among target tissues under critical life conditions. Cortisol regulates the processes of osmoregulation through a mediated increase in the activity of enzymes involved in ion metabolism, in particular, Na-K-ATPase [19]. This may indicate its stimulating role as an activator of ion-exchange enzymes, particularly in gill tissues, where the highest activity of these enzymes is observed. It should also be noted that cortisol affects the final maturation of oocytes in the preovulatory period [20]. It is believed that the deposition of cortisol by the maternal body together with its local production by the ovaries may participate in the regulation of oogenesis. There are two critical stages when cortisone can have a modulating effect on oogenesis. The first stage occurs during vitogenesis when maternal cortisol is incorporated into the yolk, and the second stage occurs during maturation and ovulation, when cortisol can play a regulatory role, causing maturation [21]. It has been shown that the stress-induced increase in cortisol, associated with a decrease in estradiol, affects the functions of granulosa cells in the follicle, worsening the quality of oocytes [15]. Recent studies suggest that this hormone may act as a key factor linking the stimuli of the social environment and the onset of sex change, initiating the transition in steroidogenesis from estrogen to androgen. In addition, there are significant differences in glucocorticoid content between marine and freshwater crustaceans. Organotin compounds at different doses can inhibit the activity of 11*beta*-hydroxysteroid dehydrogenase isoenzyme 2, which is responsible for the inactivation of cortisol, which can increase glucocorticoid levels [13, 22].

Crayfish gills play an important role in the transport of respiratory gases, excretion of nitrogen compounds and osmoregulation. The gills are the first barrier to waterborne pollutants. Gill tissue condition is generally considered a good indicator of water quality and suitable for environmental impact assessment. Its changes can lead to a decrease in oxygen consumption and a violation of the function of osmoregulation. A marked decrease in oxygen consumption can lead to internal hypoxia, which affects metabolism and movement [23].

Based on the results of the study, it was established that the level of cortisol in the gills of Procambarus virginalis increases ($p < 0.05$) (by 5.7 and 10 times) depending on age (figure 1A). In contrast, there was a probable decrease ($p < 0.05$) in the muscle of 2.2- and 3.2-fold with age, respectively (figure 1B). This is related to the distribution of energy between tissues. Cortisol is known to be involved in the development of stress reactions, regulation of water-salt balance, and carbohydrate metabolism in vertebrates, particularly fish. Significant difference between the cortisol content in roe, tissues of embryos and juveniles of the investigated crustaceans wasn't found (figure 1C). It can be assumed the hormone level changes of in this samples are related to the direct influence of the surrounding water environment.

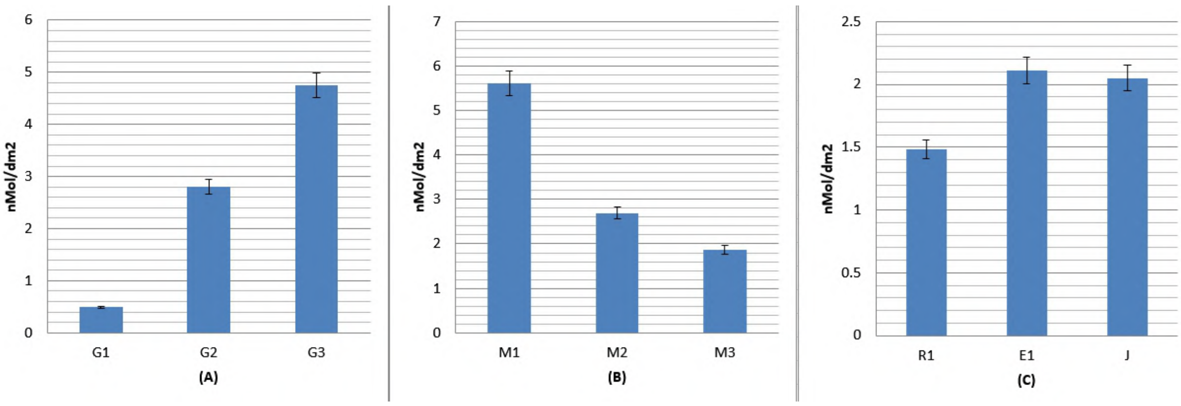

Figure 1. The content of cortisol in tissues gills (A), muscle (B), roe, embryos and juvinale (C) of marble crayfish.

4. Conclusions

The obtained results emphasize the widespread bioaccumulation of EDS, namely compounds with estrogenic activity, in aquatic invertebrates depending on the duration of exposure, which may indicate the role of the aquatic environment in the bioaccumulation of xenoestrogens. The study demonstrates the need to monitor exposure to EDC contaminants due to their effects on water quality degradation and serious toxicological effects on aquatic biota and human health to inhibit such potential. Estrogens are clearly necessary for normal fauna and human physiology but can have serious negative consequences if allowed to accumulate in the environment.

A link between chronic exposure to low concentrations of chemicals via the environment or food chain and reproductive health in animals has been demonstrated. Xenobiotics, including parent compounds and their metabolites in aquatic ecosystems, can cause developmental delay, malformations, behavioral changes, and mortality in non-target organisms.

The main source of exposure to EDCs for humans is food, particularly of animal origin. Concerns have been raised about estrogens entering the human food chain, which in turn is related to how aquatic organisms consumed as food absorb and metabolize estrogens. In epidemiological studies, EDCs have been associated with immunotoxicity and neurobehavioral deficits both in consumers of contaminated products, including aquaculture, which accumulated these substances directly from the environment and in children exposed to EDCs in utero and through breast milk. The possibility that the bioaccumulate properties of persistent organic chemicals with hormone-like activity and chronic low-level exposure may contribute to the overall risk of breast cancer in women, as well as reproductive and developmental effects in humans, has serious implications for the prevention of these diseases. If consumed at levels above safe thresholds, they can cause metabolic diseases in humans. But, taking into account the fact that hormones act at very low doses, especially during sensitive stages of life, this concept can be extrapolated to EDCs, for which the biological significance of doses of certain EDCs below regulatory "safe" levels has been shown. These findings may have serious public health implications, as exposure to EDCs is still occurring worldwide, possibly affecting future generations and leading to the development of previously unreported diseases.

The tissues of aquatic organisms may contain a mixture of several ecologically toxic compounds, in addition to endocrine-disrupting contaminants, due to the widespread contamination of surface waters with poorly treated municipal and industrial wastes. This phenomenon can have additive, synergistic or antagonistic effects, which can explain their ultimate biological activity.

Thus, it is possible to note two important aspects related to the issue of contamination of aquatic biota with compounds that cause the destruction of the endocrine system. The first aspect concerns the impact of EDCs on the reproduction of wildlife populations, including aquatic organisms, which may have a negative impact on species conservation. The second aspect is that, since the effects of EDCs are realized on humans in different ways, primarily through trophic link food chains, further research is needed for public health policy planning.

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References

[1] Garritano S, Pinto B, Calderisi M, Cirillo T, Amodio-Cocchieri R and Reali D 2006 *Environmental Health* **5**(1) 9 ISSN 1476-069X URL https://doi.org/10.1186/1476-069X-5-9
[2] Kumar M, Sarma D K, Shubham S, Kumawat M, Verma V, Prakash A and Tiwari R 2020 *Frontiers in Public Health* **8** ISSN 2296-2565 URL https://doi.org/10.3389/fpubh.2020.553850
[3] Rebuzzini P, Fabozzi G, Cimadomo D, Ubaldi F M, Rienzi L, Zuccotti M and Garagna S 2022 *Cells* **11**(19) 3163 ISSN 2073-4409 URL https://doi.org/10.3390/cells11193163
[4] Gonsioroski A, Mourikes V E and Flaws J A 2020 *International Journal of Molecular Sciences* **21**(6) 1929 ISSN 1422-0067 URL https://doi.org/10.3390/ijms21061929
[5] Lykholat T Y, Lykholat O A, Marenkov O M, Kvitko M O, Panfilova H L, Savosko V N, Belic Y V, Vyshnikina O V and Lykholat Y V 2022 *Journal of Physics: Conference Series* **2288**(1) 012013 URL https://doi.org/10.1088/1742-6596/2288/1/012013
[6] Guć M and Schroeder G 2020 *Biomolecules* **10**(5) 672 ISSN 2218-273X URL https://doi.org/10.3390/biom10050672

[7] Schröder P, Helmreich B, Škrbić B, Carballa M, Papa M, Pastore C, Emre Z, Oehmen A, Langenhoff A, Molinos M, Dvarioniene J, Huber C, Tsagarakis K P, Martinez-Lopez E, Pagano S M, Vogelsang C and Mascolo G 2016 *Environmental Science and Pollution Research* **23**(13) 12835–12866 ISSN 1614-7499 URL https://doi.org/10.1007/s11356-016-6503-x

[8] Carnevali O, Notarstefano V, Olivotto I, Graziano M, Gallo P, Di Marco Pisciottano I, Vaccari L, Mandich A, Giorgini E and Maradonna F 2017 *Aquatic Toxicology* **185** 95–104 ISSN 0166-445X URL https://doi.org/10.1016/j.aquatox.2017.02.007

[9] Tresnakova N, Kubec J, Stara A, Zuskova E, Faggio C, Kouba A and Velisek J 2022 *Biology* **11**(6) 927 ISSN 2079-7737 URL https://doi.org/10.3390/biology11060927

[10] Azevedo A, Bailey L, Bandeira V, Dehnhard M, Fonseca C, de Sousa L and Jewgenow K 2019 *PLOS ONE* **14**(8) 1–17 URL https://doi.org/10.1371/journal.pone.0221124

[11] McDonald J H 2014 *Handbook of Biolological Statistics* 3rd ed (Baltimore, Maryland: Sparky house publishing) URL https://www.biostathandbook.com/

[12] Bulmer M G 1979 *Principles of Statistics* (New York, USA: Dover Publications Inc) URL http://bobweigel.net/csi763/images/Bulmer_Principles_of_Statistics_1979_all.pdf

[13] Graceli J B, Dettogni R S, Merlo E, Niño O, da Costa C S, Zanol J F, Ríos Morris E A, Miranda-Alves L and Denicol A C 2020 *Molecular and Cellular Endocrinology* **518** 110997 ISSN 0303-7207 URL https://doi.org/10.1016/j.mce.2020.110997

[14] Lykholat T, Lykholat O and Antonyuk S 2016 *Tsitologia i genetika* **50**(1) 40–51 ISSN 0564-378 URL https://pubmed.ncbi.nlm.nih.gov/27266184/

[15] Gallo A 2022 *International Journal of Environmental Research and Public Health* **19**(3) 1303 ISSN 1660-4601 URL https://doi.org/10.3390/ijerph19031303

[16] Iromo H, Zairin Junior M, Agus S M and Manalu W 2014 *Pakistan Journal of Biotechnology* **11**(2) 79–86 URL https://pjbt.org/index.php/pjbt/article/view/499

[17] Pan J, Liu M, Chen T, Cheng Y and Wu X 2018 *Cell and Tissue Research* **373**(2) 509–520 ISSN 1432-0878 URL https://doi.org/10.1007/s00441-018-2834-x

[18] Silveyra G R, Medesani D A and Rodríguez E M 2022 *Frontiers in Physiology* **13** ISSN 1664-042X URL https://doi.org/10.3389/fphys.2022.926492

[19] Prychepa M V and Potrokhov O S 2016 *Hydrobiological Journal* **52**(3) 86–98 ISSN 0018-8166 URL https://doi.org/10.1615/HydrobJ.v52.i3.80

[20] Milla S, Wang N, Mandiki S N M and Kestemont P 2009 *Comparative Biochemistry and Physiology Part A: Molecular & Integrative Physiology* **153**(3) 242–251 ISSN 1095-6433 URL https://doi.org/10.1016/j.cbpa.2009.02.027

[21] Faught E and Vijayan M M 2018 *Fish and Fisheries* **19**(6) 1016–1030 URL https://doi.org/10.1111/faf.12309

[22] Goikoetxea A, Todd E V and Gemmell N J 2017 *Reproduction* **154**(6) 149–160 URL https://doi.org/10.1530/REP-17-0408

[23] Velisek J, Stara A, Kubec J, Zuskova E, Buric M and Kouba A 2020 *Scientific Reports* **10**(1) 875 ISSN 2045-2322 URL https://doi.org/10.1038/s41598-020-57740-1

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Biodiversity assessment of the Danube region as a tool for the development of protected areas in the region

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Biodiversity assessment of the Danube region as a tool for the development of protected areas in the region

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Abstract. The paper uses the method of geospatial biodiversity assessment in the Danube region based on an expert evaluation of the distribution of species richness of fish, amphibians, reptiles, birds and mammals. The 10-point grading scale was used to evaluate the number of species in 200 sample plots of the study region. Points from 1 to 10 were separately calculated for the species in each taxonomic group. The analysis showed a close relationship between the Lower Danube floodplain and the small steppe river basins, which together make up a single natural region. A practical testing of the geospatial assessment of the species richness was done for the first time in the Danube region. An important applied result of the research is the opportunity to assess missing elements in the environmental network of the region. This approach will justify the need to designate various types of protected areas, both at the national level (natural reserves) and at the international level (the Emerald network sites and wetlands). The areas could further be used to develop a unified ecological framework, thus contributing to the protection of rare and endangered species of the region.

1. Introduction

The conservation, and moreover the restoration of biodiversity, is one of the global environmental challenges facing humanity. For Ukraine, with its valuable natural regions, such as the Carpathians, Crimea, Danube, Polissia and others, the biodiversity assessment is an initial step in deciding the further conservation strategy.

The Danube region is regarded as one of the valuable regions in terms of biodiversity, but traditionally considered in a narrow aspect, only within the boundaries of the Danube Delta. Based on the centuries-old history of the reciprocal development of the delta, the sea shelf and the mainland, in this paper we consider the Danube region in a broader aspect, taking into account the past natural connection of the small steppe rivers of the region and the Danube lakes with the unique Danube delta.

The history of biodiversity studies in the Danube Delta has a long tradition [1–3]. Nevertheless, only a few works are dedicated to the biodiversity components of the other areas of the Danube region [4, 5].

Until recently, biodiversity assessment was based on the absolute values of the number of species and their abundance, as well as on various indices of species abundance and biodiversity in general. However, the possibility of using geospatial biodiversity assessment has significantly expanded the practical application of the obtained data. Nowadays, the methods of geoinformation systems are widely applied for biodiversity analysis all over the world [6–11]. As a result, these approaches significantly increase the effectiveness of protected area planning [12–14].

The *purpose* of this research is a spatial assessment of the biological diversity of the Danube region by the example of zoological taxa and the development of a methodological approach for such work.

2. Study area, material and methods

We consider the Danube region as a combination of the small steppe river basins, the left tributaries of the Danube in the lower reaches, and a chain of their final reservoirs (the Danube lakes, which used to be estuaries): Kahul, Kartal, Kuhurlui, Yalpuh, Katlabuh, Kytai and adjacent areas of the Lower Danube (figure 1). The region is studied within the administrative boundaries of Ukraine, so the basins of some small steppe rivers are not fully included. As the runoff of such small rivers as the Kohylnyk and Sarata affects Zhebrianska Bay with its rich flora and fauna (the Danube avandelta), their basins and Sasyk Reservoir are included in this natural region. The total study area covered 975,425 ha. The region is characterised by complex ecological relationships among various natural components and their mutual influence.

The Danube River, with its unique and fastest-growing delta in Southeast Europe, is a pivot

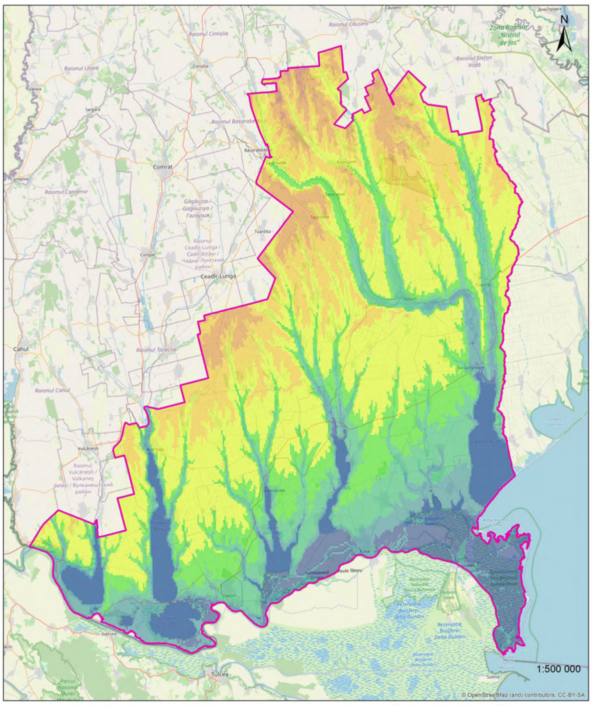

Figure 1. The study area.

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of the region. Together with the adjacent small river basins, they have formed a valuable natural community with different landscape types that contribute to the development of rich biodiversity. However, the delta and its adjacent areas have also suffered from considerable man-made transformation. Vast coastal areas were embanked and converted into agricultural lands. Small rivers were transformed into a set of reservoirs, ponds and canals. Canals and hydrotechnical facilities were intensively built, focusing on transporting the Danube water to various parts of the region. Most of these activities had a negative impact on the integrity of natural communities and led to a decrease in regional species abundance.

Vertebrate taxa such as fish, reptiles, amphibians, birds, and mammals (except for Chiroptera) were chosen as biodiversity indicators. Compared with other taxa, they are more often on top of the ecological pyramid and are sensitive to the slightest changes in ecosystems. Their status makes it easier to judge the environmental processes in the natural region, and the concentration of their species abundance can diagnose the degree of importance or transformation of various spatial areas.

The assessment of selective zoological diversity is based on the results of regional fieldwork carried out during 1970-2022.

A grading scale for species abundance within each taxon was developed to assess diversity. First, each type of taxon was associated with its own habitat. Then, using QGIS methods, a regular grid was made for the region, consisting of 200 hexagons, each with an area of about 5 thousand hectares. According to the ratio of habitats in one or another hexagonal polygon, a quantitative assessment of the species abundance for a particular taxon in the polygon was made. Given the significant differences in species abundance among birds, reptiles, amphibians, fish and mammals, ranked scores were determined for each taxon to standardise and align the obtained data. For this purpose, the share of species abundance in a given hexagon was correlated with the total species abundance of a given taxon in the region. Based on the scores in each taxon, a table of the integral zoological value of the species abundance in each polygon was formed. Therefore, the data from zoological studies were correlated with the obtained regular grid. For the integral assessment, the method of heat maps was also used in accordance with the scores within the hexagon, which, on the one side, gives a smoother picture, and on another side, reliably identifies the most critical parts of the region.

The analysis of the region transformation used the open data on land use classification posted by the European Space Agency “ESA WorldCover” [15]. According to this classification, the following types of land surface with different land use are distinguished in the Danube region: 1) tree vegetation; 2) shrub vegetation; 3) herbaceous vegetation; 4) agricultural land; 5) buildings; 6) areas without vegetation or with sparse vegetation; 7) reservoirs with a permanent presence of water; 8) wetlands and reservoirs overgrown with vegetation. We also classified types 4 and 5 as significantly transformed and the remaining ones as natural and semi-natural.

Spatial analysis was conducted using the QGIS software.

3. Results

Based on the developed method, we have received maps of species abundance for some taxonomic groups in the Danube region (figures 2-5). Colour gradation shows the score range of species diversity: dark green (1), light green (2-3), yellow (4-5), orange (6-8) and bright red (9-10 points).

There are some peculiarities in the distribution of fish species abundance in the region (figure 2). Thus, the Danube floodplain houses the highest species diversity. In most drainage basins, the fish species composition is extremely poor. Small rivers are drying up, but the embanked areas still preserve some species abundance in their middle reaches. Only in the Kohylnyk and Sarata rivers (the easternmost ones in the figure), the water content of which is

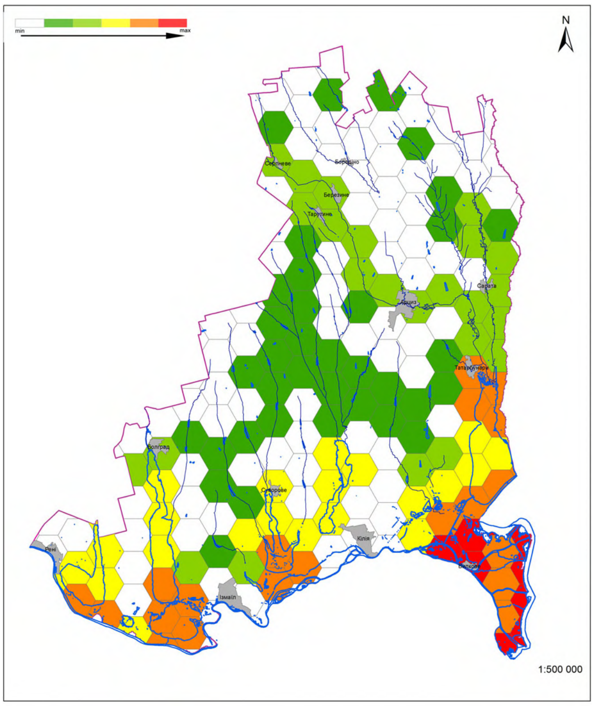

Figure 2. Abundance of fish species.

higher, relatively low species diversity persists throughout the entire length of their channels (the Kohylnyk River) almost to the regional borders.

The highest diversity index of reptiles and amphibians is recorded in the Danube floodplain (figure 3) as all the amphibian species typical for the region are available there, along with water reptiles (the European pond turtle *Emysor bicularis* Linnaeus, 1758, dice snake *Natrix tessellata* Laurenti, 1768, grass snake *Natrix natrix* Linnaeus, 1758). Suitable habitats for reptiles and amphibians are located not only along the slope landscapes of small rivers but also along numerous forest belts in agricultural lands that ensure a much wider distribution of the optimal species composition of reptiles compared with fish in the middle reaches of small steppe rivers.

Birds form the basis of the species richness of vertebrates in the region (figure 4). The avian diversity is represented by more than 320 species. A deeper colour of the Danube floodplain indicates the predominance of waterbirds, although their distribution is limited along small rivers. The species composition of this taxonomic group is very dynamic and depends on the landscape diversity and seasonality. Birds, due to their plasticity and mobility affected by external factors can quickly disperse within the Danube region of Ukraine and outside its boundaries.

The areas of high mammal biodiversity (figure 5) are concentrated in latitudinal zones along the Danube floodplain and in the north of the region. This diversity is most affected by the heterogeneity of landscapes and habitats. Thus, the northern part of the Danube region is located on the elevation, streaked with channels of small rivers, gullies and ravines, with vast Tarutinska Steppe and forest tracts. This determines the high species diversity of mammals, mainly rodents (Rodentia). The landscapes of the Danube floodplain are highly mosaic, with large areas of riverine forests, meadow ecosystems and floodplain lakes that ensures a high species abundance of all orders of mammals typical for the region. Moreover, the inaccessibility of the territory together with the border control and environmental regimes, contribute to the

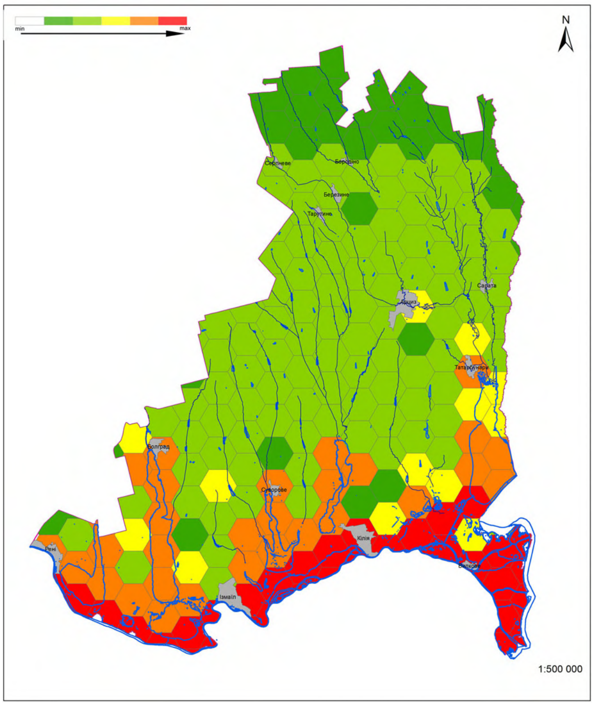

Figure 3. Abundance of herpeto- and batrachofauna species.

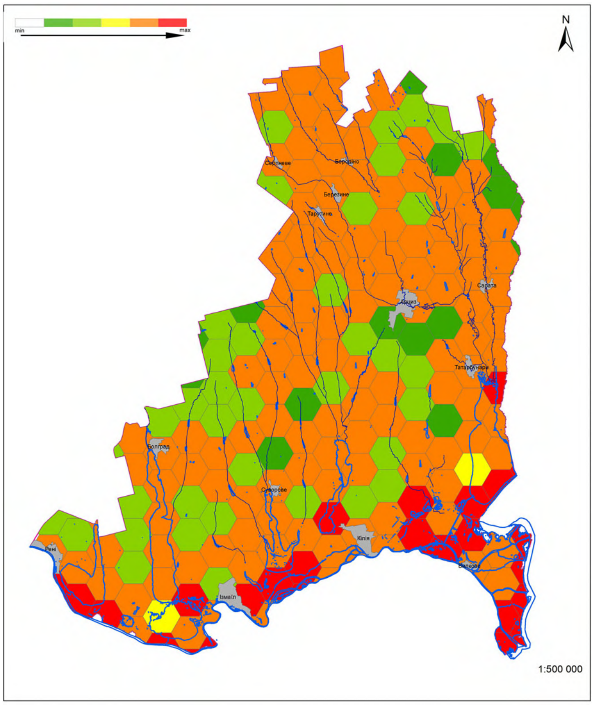

Figure 4. Abundance of avifauna species.

conservation of biodiversity.

An integrated assessment of the whole zoological diversity (figure 6) quite fully illustrates the cohesion of this natural region, the absence of any hiatuses and clear latitudinal demarcation

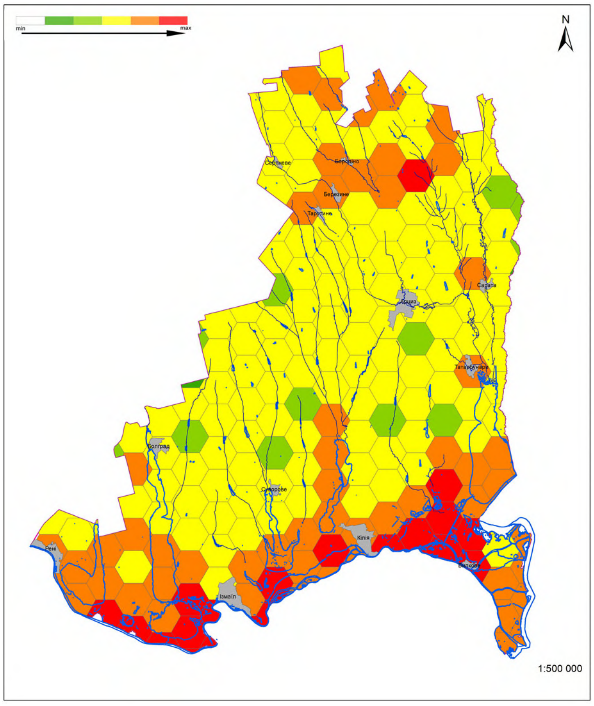

Figure 5. Abundance of mammal species.

lines from the stripes of hexagons with low species abundance, including the transition from the Danube floodplain to the small steppe basins. This is especially pronounced when species diversity within the ecological framework is reflected using GIS grids. However, some biodiversity loss is recorded in the interfluvial areas and the middle reaches of the rivers flowing into Lake Katlabuh and Stensivsko-Zhebrianski Plavni.

4. Discussion

Geospatial assessment of the ichthyofauna species diversity (figure 2) clearly shows the consequences of water flow regulation in small rivers, or more precisely in their intermediate reservoirs of the Danube lakes and, consequently, almost complete isolation of them from the Danube floodplain, especially during floods. It has caused a rapid depletion of the ichthyofauna in the lakes and rivers, formerly used for upstream migration by spawning shoals of semi-anadromous fish species. More than half a century of isolation led to a decrease in the previous abundance of fish species. The current negative situation can only be solved if the water exchange between the basins of small rivers and the Danube floodplain is restored. It will improve the water content of small rivers and progressively restore their slopes and the underground springs blocked by layers of landslide soils.

The concentration of a high diversity of amphibians, reptiles and mammals in the Danube floodplain (figures 3, 5) indicates the need to restore the channels and slope sections of small rivers. Acting as ecological corridors, they will promote the unimpeded dispersal of species in the meridional and latitudinal directions. Otherwise, it is impossible to maintain the population homeostasis of representatives of the batracho-, herpeto- and mammal fauna, predominantly rare and vulnerable species.

Birds, as the most mobile zoological component of biodiversity, easily colonise well-preserved discrete natural areas along the floodplains and slopes of small rivers (table 1), thus determining the "elongation" of integral grids of optimal and high species diversity along the channel sections

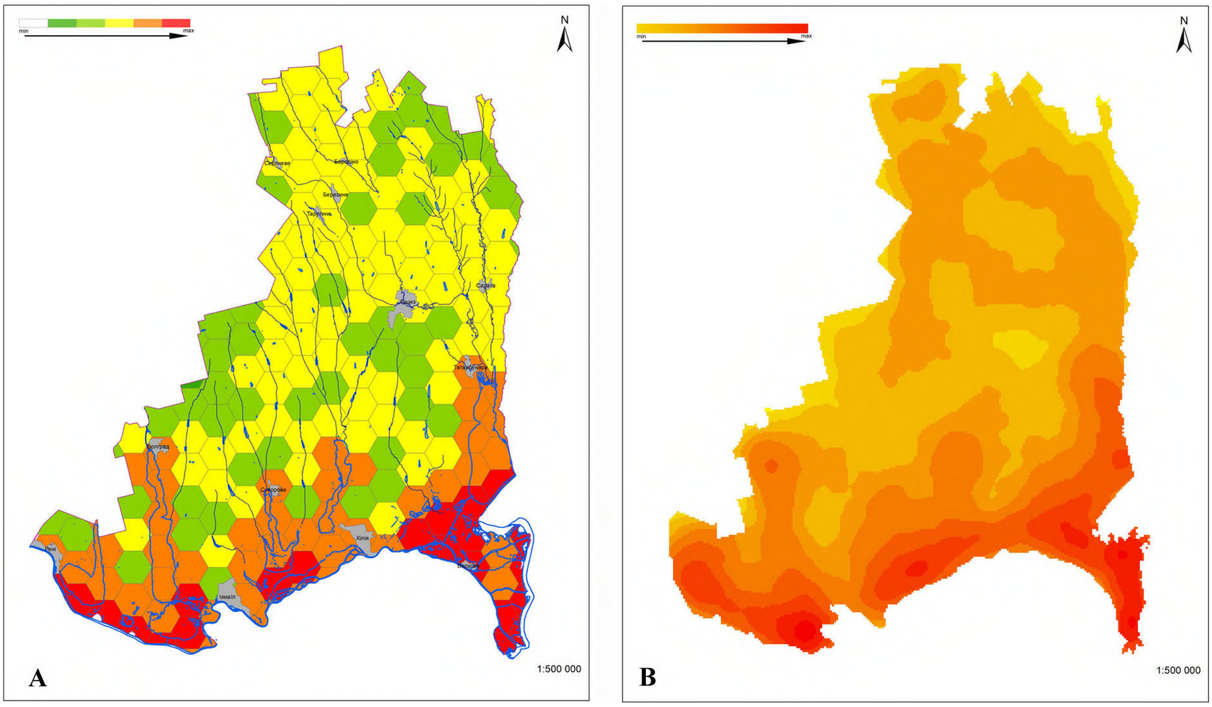

Figure 6. Integral assessment of the abundance of zoological species (A – regular hexagons; B – grids of integral diversity).

of small rivers in figure 6B.

Table 1. The share of natural habitats, in percent of the total area of riverine-floodplain habitats of the main steppe rivers in the Danube region.

Main rivers of the basin	Name of the basin	Percent of natural habitats
Kahul	Lake Kahul	58.5
Velykyi Yalpuh	Lake Yalpuh	82.7
Velykyi Katlabuh	Lake Katlabuh	56.8
Kyrgizh-Kytai	Lake Kytai	60.1
Drakulia	Stensivsko-Zhebrianski Plavni	44.9
Kohylnyk	Sasyk Reservoir	70.6

The preserved natural state of some channels and floodplains of small rivers supports the survival of many animal species, including Ukrainian red-listed ones, thereby enabling the potential expansion of the genetic exchange corridors between fragmented populations and subpopulations of animals (except birds).

However, the critical destruction of steppe and meadow areas, converted to agricultural lands, has led to the loss of many stenobiont animal species. In general, the noticeable predominance of anthropogenically transformed lands and the isolation of individual natural areas hamper the protection of regional species diversity. An essential element of biodiversity conservation in natural communities is the network of protected sites with different statuses. The region encompasses protected areas of national significance, wetlands of international importance and the Emerald network sites. The regional ecological network is also developed, focusing on integrating valuable areas (cores) into a single system through ecological corridors.

The available data on the biodiversity distribution and existing boundaries of natural conservation areas enable the identification of gaps and the development of a more effective system of protected sites. The data analysis indicates the need to designate three new wildlife reserves and significantly expand the regional ecological network. Total area recommended for the nature conservation areas is 45,934 ha.

This approach will facilitate the complete restoration of the mutual influence between the Lower Danube floodplain and small steppe rivers, expand ecological corridors and biodiversity cores, and contribute to the conservation of fauna populations of this unique natural region.

5. Conclusions

A large-scale geospatial assessment of the Danube region biodiversity has allowed identifying the most valuable areas, naturally located in the Danube Delta and the lower part of the Danube lakes, and the areas with an urgent need of restoration.

A holistic view of the region also showed the role of small steppe rivers in the species exchange and the formation of ecological corridors. The dominance of the Lower Danube floodplain in terms of the animal species abundance may also be associated with the availability of protected areas of different statuses.

Despite the significant transformation of the region (a high percentage of agricultural land use, embankment of the Danube lakes-estuaries, conversion of some sections of small river channels, the Danube region still remains an important area for biodiversity conservation, not only in its key part - the Danube Delta, but also within the boundaries of the adjacent small river basins.

The use of a holistic spatial approach to biodiversity assessment provides wide opportunities for management decision-making, such as identifying potential protected areas, areas for restoration, etc. The data analysis indicates the need to designate three reserves with a total area of 18,178 ha and expand ecological corridors with a total area of 27,756 ha.

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References

[1] Voinstvenskyi M A 1953 *Proceedings of Zoological Museum of Kyiv University* **12**(3) 49–72
[2] Averin Y V 1960 *Bulletin of Moscow Society of Naturalists, Biological Section* **65**(2) 5–12
[3] Shelyag-Sosonko Y P (ed) 1999 *Biodiversity of the Danube Biosphere Reserve, conservation and management* (Kyiv: Naukova Dumka)
[4] Panchenko V A and Balatsky K L 1991 Rare and endangered birds of the danube and dniester deltas and adjacent areas *Rare birds of the Black Sea region* ed Koshelev A I, Korzyukov A I, Lobkov V A and Peresad’ko L V (Kyiv-Odessa: Lybid) pp 37–53
[5] Korzyukov A I, Rusev I T and Yakovlev M V 2005 The lower reaches of the kagilnik river as an important bird area *Current problems of zoology and ecology. Proceedings of the international conference dedicated to the 140th anniversary of the foundation of I I Mechnikov Odessa National University, Department of*

Zoology of ONU, Zoological Museum of ONU and the 120th anniversary since the birth of the Honored Scientist of the Ukrainian SSR, Prof. I I Puzanov (Odessa: Feniks) pp 293–295

[6] Salem B B 2003 *Journal of Arid Environments* **54**(1) 91–114 URL https://doi.org/10.1006/jare.2001.0887

[7] Murthy M S R, Giriraj A and Dutt C B S 2003 *Biol lett* **40**(2) 75–100 URL https://www.researchgate.net/publication/228647946

[8] Monavari S and Momen Bellah Fard S 2010 *International Journal of Environmental Research* **4**(4) 701–712 ISSN 1735-6865 URL https://ijer.ut.ac.ir/article_256.html

[9] Mumladze L, Japoshvili B and Anderson E P 2020 *Biologia* **75**(9) 1385–1397 ISSN 1336-9563 URL https://doi.org/10.2478/s11756-019-00398-6

[10] Chiaverini L, Macdonald D W, Bothwell H M, Hearn A J, Cheyne S M, Haidir I, Hunter L T B, Kaszta Ż, Macdonald E A, Ross J and Cushman S A 2022 *Animal Conservation* **25**(5) 660–679 URL https://doi.org/10.1111/acv.12771

[11] Mokany K, Ware C, Harwood T D, Schmidt R K and Ferrier S 2022 *Conservation Biology* **36**(5) e13915 URL https://doi.org/10.1111/cobi.13915

[12] Geneletti D and van Duren I 2008 *Landscape and Urban Planning* **85**(2) 97–110 ISSN 0169-2046 URL https://doi.org/10.1016/j.landurbplan.2007.10.004

[13] Baral H, Keenan R J, Sharma S K, Stork N E and Kasel S 2014 *Ecological Indicators* **36** 552–562 ISSN 1470-160X URL https://doi.org/10.1016/j.ecolind.2013.09.022

[14] Tezel D, Inam S and Kocaman S 2020 *ISPRS International Journal of Geo-Information* **9**(2) 91 ISSN 2220-9964 URL https://doi.org/10.3390/ijgi9020091

[15] Zanaga D, Van De Kerchove R, Daems D, De Keersmaecker W, Brockmann C, Kirches G, Wevers J, Cartus O, Santoro M, Fritz S, Lesiv M, Herold M, Tsendbazar N E, Xu P, Ramoino F and Arino O 2022 ESA WorldCover 10 m 2021 v200 URL https://doi.org/10.5281/zenodo.7254221

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Seeds' similarity of cultural and natural flora under chloride load in conditions of southern Ukraine

Seeds' similarity of cultural and natural flora under chloride load in conditions of southern Ukraine

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Abstract. Saline soils make up almost 25% of the entire earth's surface. Their areas, unfortunately, have a steady tendency to expand due to the aridization of the climate and the global increase in the average annual air temperature of the planet. The increased concentration of salts in the soil limits the diversity of cultural and conditions the poverty of natural flora, forms areas of risky agriculture in the south of Ukraine. Seeds are a unique product of evolution, the main generative organ of plants, characterized by a number of morphological, physiological and biological features, among which there is adaptation heterogeneity. It is established that by the number of germination days (the seeds of the cultural flora sprouts for 7–10 days, and in wild representatives this indicator extends to 10–12 days) the plants can be arranged in the following order: seven days –*Secale cereale* L., *Triticum durum* L., *Avena sativa* L., *Hordeum vulgare* L., *Helianthus annuus* L., *Matricaria recutita* L.; ten days – *Beta vulgaris* L., *Phaseolus vulgaris* L. and twelve days – *Valeriana officinalis* L. It is found that the most optimal for germination is the aquatic environment, so the plants are arranged according to the list: *Helianthus annuus* L. → *Avena sativa* L. → *Triticum durum* L. → *Matricaria recutita* L. → *Secale cereale* L. → *Hordeum vulgare* L. → *Beta vulgaris* L. → *Valeriana officinalis* L. → *Phaseolus vulgaris* L. It is proved that Na+ and Cl–ions differentially affect the seed germination energy: at a concentration of 0.1% NaCl – *Triticum durum* L. → *Helianthus annuus* L. → *Hordeum vulgare* L. → *Secale cereale* L. → *Phaseolus vulgaris* L. → *Avena sativa* L. → *Matricaria recutita* L. → *Beta vulgaris* L. → *Valeriana officinalis* L.; at a solution concentration of 0.2% NaCl – *Secale cereale* L. → *Triticum durum* L. → *Helianthus annuus* L. → *Avena sativa* L. → *Matricaria recutita* L. → *Hordeum vulgare* L. → *Phaseolus vulgaris* L. → *Valeriana officinalis* L. → *Beta vulgaris* L. The results obtained indicate that the chloride load in the seeds of plants manifests itself in the form of distress as well as eustress. It has been proved that the diagnostic features of chloride hermesis were more clearly manifested in the representatives of the cultural flora than the natural ones.

1. Introduction

Due to increasing anthropogenic pressure on the environment, the climatic conditions on the planet Earth are changing [1]. Saline soils make up almost 25% of the earth's surface (about

$9 \cdot 10^8$ ha). Unfortunately, their areas tend to expand due to climate aridization and an increase in the average annual temperature of the planet [2, 3]. In Ukraine, about 1 million hectares of land have varying degrees of soil salinization. The south of Ukraine forms a zone of risky agriculture characterized by temperate continental climate with hot summers, high solar insolation and significant water deficit [4, 5]. Poverty and specificity of both natural and cultural flora is conditioned by the presence of the sea area (sea, estuaries), intensive evaporation of water during irrigation, soil salinization [6, 7]. Seeds are a unique product of evolution, the main generative organ of plants, characterized by a number of morphological, physiological and biological features, among which there is adaptation heterogeneity [8, 9]. Therefore, research on the similarity of plant seeds to salt stress is becoming increasingly relevant.

Hence, the *research aim* is to find out the seeds' similarity of natural and cultural flora under chloride load in southern Ukraine.

2. Material and methods

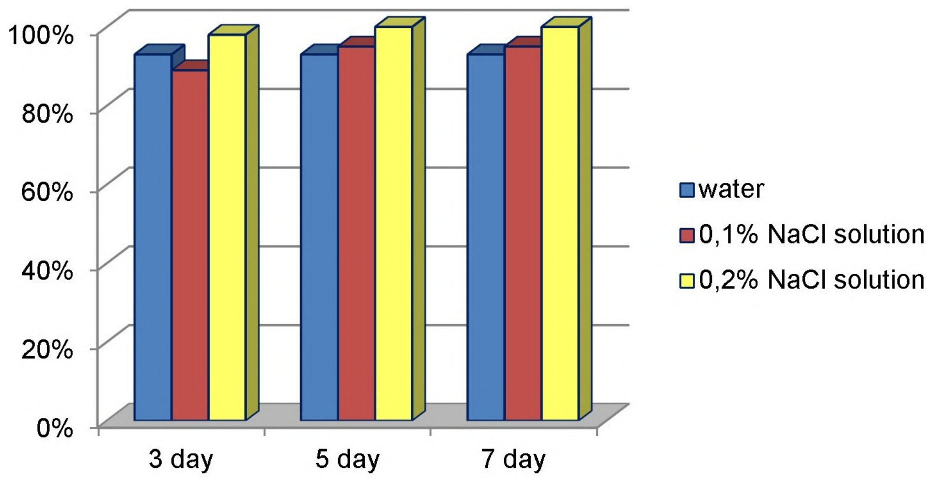
The researches object was the seeds of the following plant species that prevail in the herbaceous cultivated and wild vegetation of southern Ukraine: *Beta vulgaris* L., *Secale cereale* L., *Triticum durum* L., *Avena sativa* L., *Phaseolus vulgaris* L., *Hordeum vulgare* L., *Helianthus annuus* L., *Valeriana officinalis* L., *Matricaria recutita* L. The artificial level of salinity in the laboratory and vegetation conditions was created by adding the appropriate amount of salt to the water when wetting and subsequent irrigation according to the scheme: K – natural conditions, option 1 – vegetation and laboratory control (growing seeds in water), option 2 – growing in 0.1% NaCl salt solution, option 3 – growing in 0.2% NaCl salt solution of. The choice of concentration of chloride salts is explained by the fact that such percentage is considered stressful for seeds [4, 10]. Representatives of cultural flora are hybrids and varieties, which are located in the south of Ukraine [6]. The seeds of the experimental plants of the wild flora were collected from hills associations of Zaporizhzhya region (Bogatyr, Terpinnia). The physiological aspects of determining the germination energy of the experimental plants and their similarity were performed according to conventional methods [9]. Laboratory and vegetation experiments were conducted on the basis of the Bogdan Khmelnitsky Melitopol State Pedagogical University, and the field experiments on the basis of Novotroitsky Farm "Niva". Statistical analysis of the obtained data was performed using Microsoft Excel and Statistica 8.0. For comparison of samples, arithmetic mean (M) and standard error from mean (SEM) were calculated. The difference $p \leqslant 0.05$ was considered statistically significant for all indicators.

3. Results

Due to the irrigation of crops, the number of saline soils is increasing annually [6, 11]. Therefore, the study of the adaptive capacity of seeds of representatives of natural and cultural flora to different concentrations of chloride salts will bring us closer to understanding the strategy of adaptive transformations.

The obtained experimental data showed that the seeds of *Secale cereale* L. sprouted 93% in aqueous solution for 3 days (figure 1, A), 89% – in 0.1% NaCl solution, 95% – in 0.2% NaCl solution. At 5 days, this indicator had the following values: in aqueous solution – 93%, in 0.1% NaCl solution – 95%, in 0.2% NaCl solution the number of sprouted seeds increased to 100%. At 7 days, the percentage of seed germination did not change. Our data are in agreement with the opinion of several authors [12], that cereals during germination have a classic effect of gibberellins, associated with the release of seeds from a resting state, and gibberellin "start" formation of amylases is a prerequisite for germination.

The experimental data (figure 1, B) showed that the seeds of *Triticum durum* L. sprouted well in NaCl solutions with a concentration of 0.1% and 0.2% by the third day. It is shown that in the aquatic environment 98% of the seeds sprouted on the 3rd day; the percentage did not



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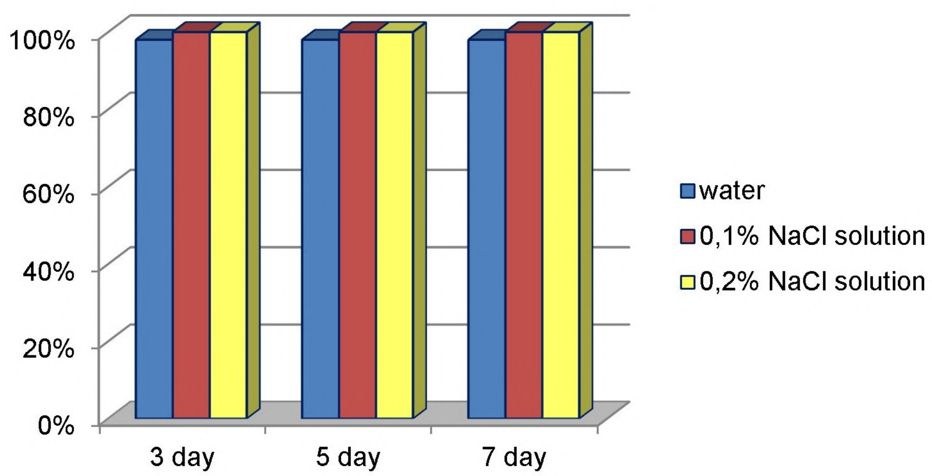


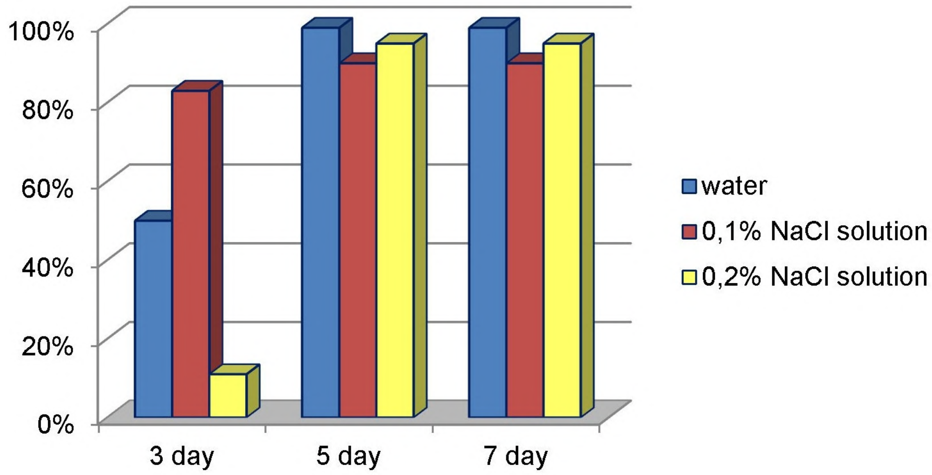
B

Figure 1. Seed germination energy (%): A – Secale cereal L., B – *Triticum durum* L.

change on the 5th and 7th days. In NaCl solutions with a concentration of 0.1% and 0.2% 100% of the seedlings sprouted on the third day, which may be due to the activation of protective reactions under the action of lections [13], gibberellins, which stimulate the processes of grain germination [14].

Seed germination of *Avena sativa* L. (figure 2, A) showed that on the 3rd day the number of sprouted seeds in water was 50%, on the 5th and 7th day it increased to 99%. In 0.1% NaCl solution on the third day germinated – 83%, the fifth and the seventh – 90%, but in 0.2% NaCl solution on the third day – 11% of seeds, the fifth and the seventh – 95%. During the seven–day period, the largest amount of seeds sprouted in water, although on day 3; 0.1% NaCl solution was the best conditions for the seeds. Germination was more stable in 0.2% NaCl solution. It is known that lections are involved in the process of seed germination and ripening [13].

The obtained results proved that the germination of seeds of *Hordeum vulgare* L. began on the third day (figure 2, B), with the highest values observed in 0.1% NaCl solution – 95%, in the aquatic environment – 93%. This pattern remained for the fifth and seventh days of the experiment. In 0.2% NaCl solution, the smallest number of grains sprouted: 23% on the third day, and on the fifth and seventh – 88%. The faster the germination process occurred with the



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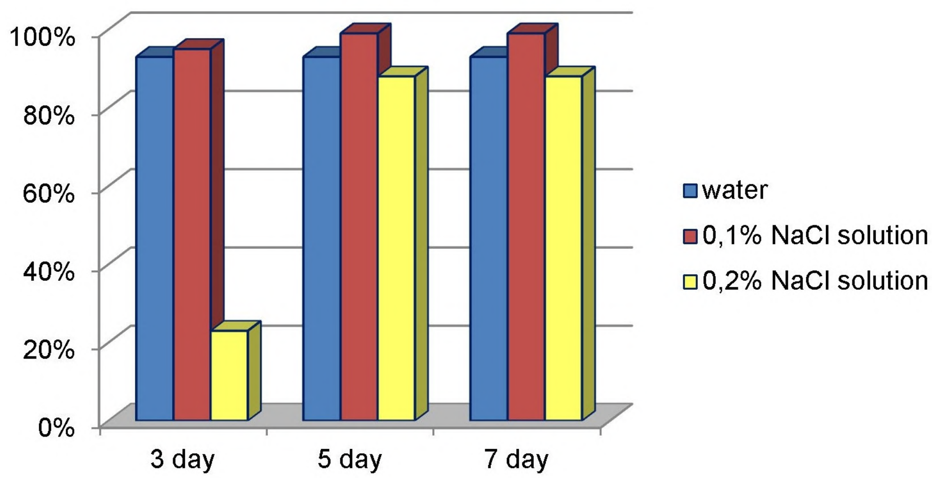


B

Figure 2. Seed germination energy (%): A – *Avena sativa* L., B – *Hordeum vulgare* L.

seeds that germinated in water, the longer the germination occurred in solutions.

Thus, our results illustrated that Na^+ and Cl^- ions at 0.1% concentration stimulate seed germination for the third day after sowing, this position is confirmed by the works of several authors [7, 11]. Water, penetrating through the pollen and the skin into the intercellular spaces and cells, removes the seed germ from a state of rest. Organic compounds present in the endosperm undergo certain changes, in particular, increased respiration and activated enzymes, under the influence of which the spare substances are converted into easily digestible forms.

It has been proved [9, 14] that in cereals during germination there is a classical effect of gibberellins associated with the release of seeds from rest. After the seeds absorb through the micropyle of water, the embryo in the area of the shield begins to synthesize GA3, GA4 gibberellins, which are transported to the aleurone layer surrounding the endosperm, and stimulate the formation of hydrolytic enzymes (α–amylases, etc.). Enzymes begin to break down the spare starch of the endosperm to the simple sugars used for embryo growth and development. Thus, gibberellin "start" formation of amylases is a prerequisite for seed germination. The mechanism of this process is not fully understood. Gibberellins are thought to stimulate amylase–specific m–RNA synthesis.

Our studies showed that during the germination of *Beta vulgaris* L. seeds (figure 3): the first sprouts appeared on the fifth day in pure water – up to 30%, in 0.1% NaCl solution – up to 20% and the smallest amount was observed in 0.2% NaCl solution – up to 2%. On the 7th day the highest amount of seeds sprouted in water was 70%, 60% in 0.1% NaCl solution, and the smallest in 0.2% NaCl solution up to 30%. On the tenth day the most seeds germinated in water 80%, 75% in 0.1% NaCl solution, and in 0.2% NaCl solution – 35%. Therefore, in *Beta vulgaris* L., the best germination occurs in water and in 0.2% NaCl solution the worst.

It is found that the seedlings of *Phaseolus vulgaris* L. began to appear on the third day (figure 4) in the sample with water and in 0.1% NaCl solution. Up to 50% of seeds have sprouted in the aqueous medium for 5 days, less than 40% in 0.1% NaCl solution, and 20% in 0.2% ones. On the seventh day, in all samples, the number of sprouted seeds increased: 60% – in water, 65% – in 0.1% saline, 45% – in 0.2% NaCl solution. El Amrani et al [15] have investigated the physiological role of seed lections – phytohemagglutinin (PHA). The protective role of PHA in germination of seeds, based on the ability of lection to be released into the environment, and, due to specific interaction with the constituent cell walls of pathogenic bacteria, is shown to cause a delay in their growth.

According to the results of germination of seeds of *Helianthus annuus* L. it was found that for 3 days the most seeds germinated in aqueous medium, in 0.1% NaCl solution – 60%, 0.2% NaCl solution – more than 20% (figure 5). On the fifth and seventh days, 100% of the seeds sprouted in all samples. Consequently, low–concentration salt solutions at the initial stage of germination promote rapid unfolding of physiological and biochemical processes in seeds [12]. It is proved that the rate of germination of *Helianthus annuus* L. seeds is characterized by inversely proportional dependence on the salt concentration in the medium.

Analysis of the experimental results obtained from germination of *Valeriana officinalis* L. seeds (figure 6, A) showed that by 3 days the highest amount of 20% sprouted in 0.2% NaCl solution, the smallest in water (10%) and 0.1% NaCl solution (0%), on the fifth day of the seeds is located in aqueous medium and solution of salts with a concentration of 0.1% NaCl the percentage of germination did not change, but 20% reached the germination energy in saline solution of 0.2% NaCl. Seed germination of *Valeriana officinalis* L. was observed for twelve days, but during this period the highest values were obtained in the aquatic environment, the lowest – in 0.1% and 0.2% saline solutions. Therefore, it can be assumed that, under the action of water, the seed cell enzymes have gone from an inactive state to an active and insoluble

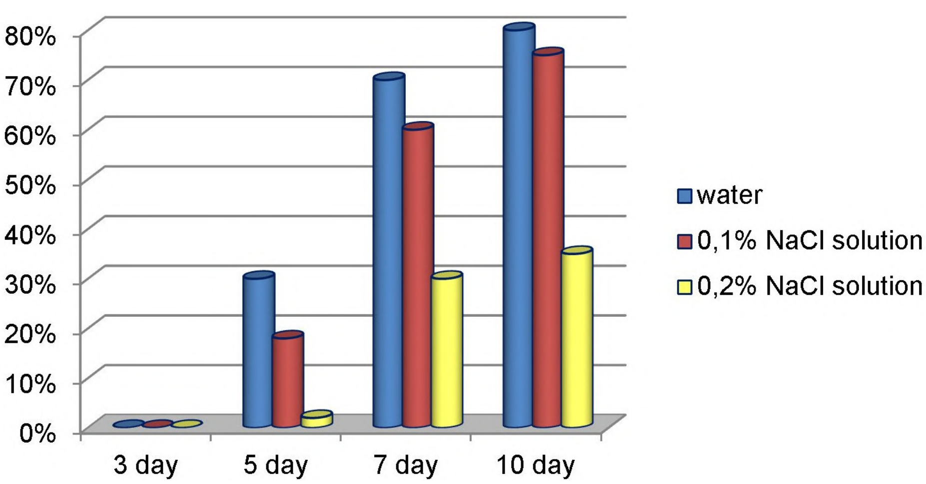


Figure 3. *Beta vulgaris* L. seed germination energy (%).

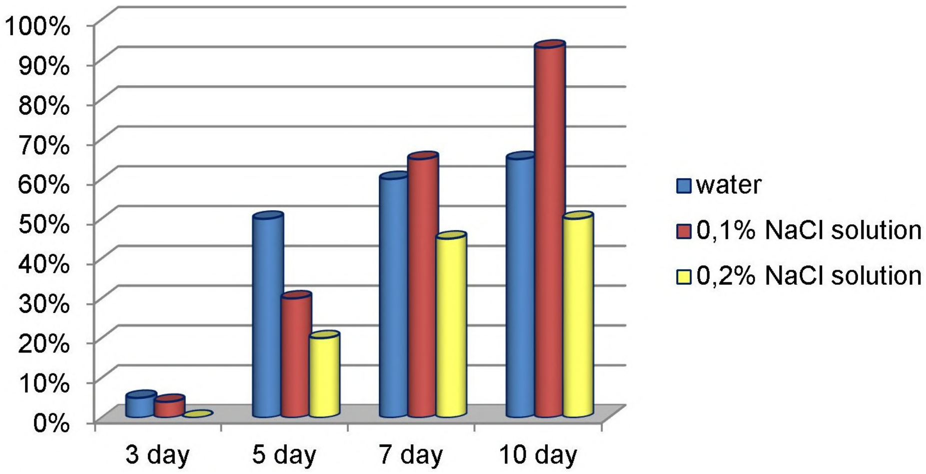


Figure 4. Germination energy of *Phaseolus vulgaris* L. seeds (%).

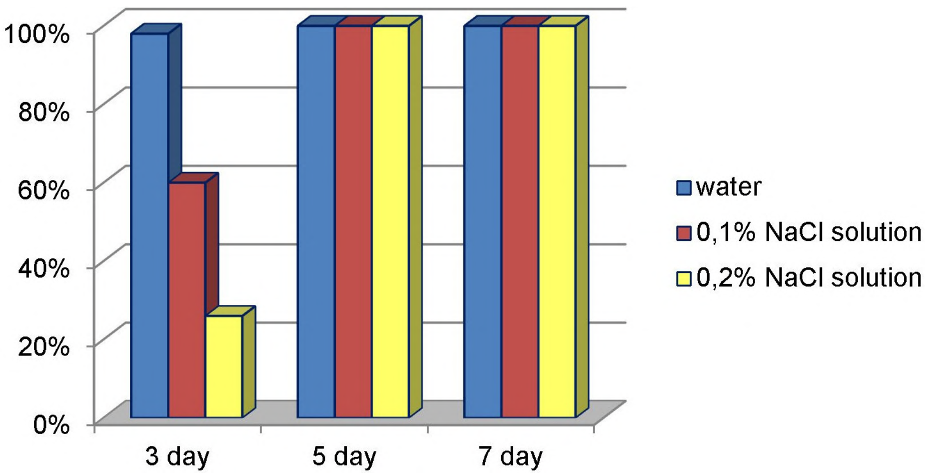


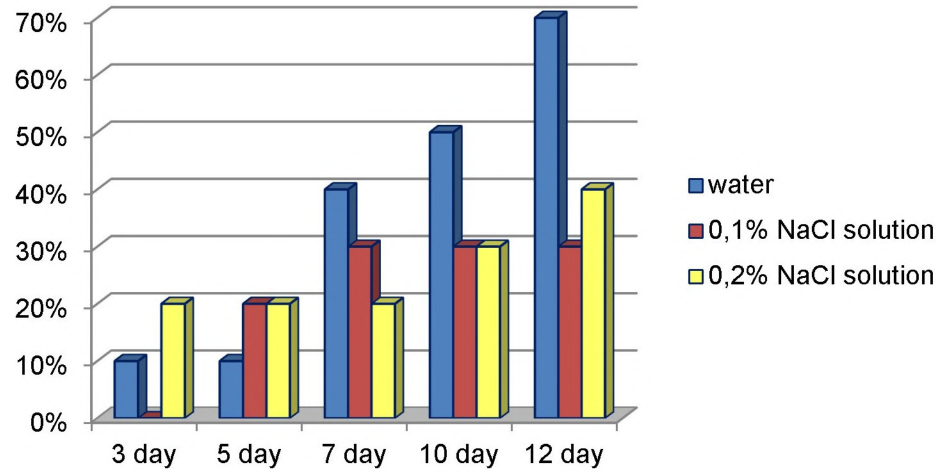
Figure 5. Germination energy of *Helianthus annuus* L. seeds (%).

spare substances have become soluble (starch – into sugar, fats – into glycerol and fatty acids, proteins – into amino acids). The embryo, using soluble organic compounds, began active growth and development [3].

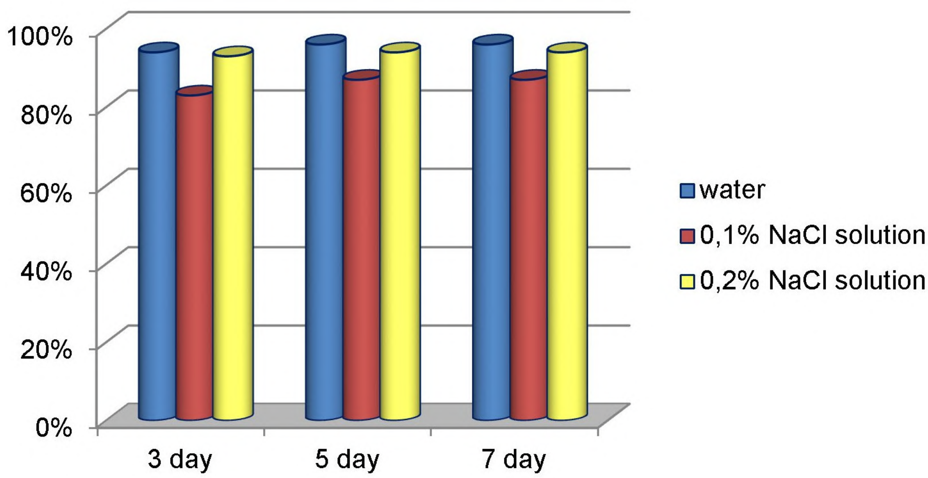
The results of germination of *Matricaria recutita* L. seeds in water; 0.1% and 0.2% NaCl solutions had the following values: on the third day the seeds germinated intensively in the aquatic environment and were more than 90%, less intensive germination occurred in 0.2% solution salts – more than 93%, the lowest amount of 83% was observed in 0.1% NaCl solution (figure 6, B).

On the 5th day in water, the percentage was more than 95% in the aqueous medium, in 0.2% NaCl solution – 94%; in 0.1% NaCl solution – more than 85%. At 7 days the number of germinated seeds in the studied media did not change. For the entire germination period, which was seven days, the highest values were observed in water, the average values were in 0.2% NaCl solution and the lowest values were in 0.1% NaCl solution. This is explained by the fact that when germination of seeds in water and solutions of salts with different concentrations, gibberellins are activated in different periods of growth and development [13, 16].

The analysis of the results shows that the stress tolerance of plant seeds to salinization



A



B

Figure 6. Seed germination energy (%): A – *Valeriana officinalis* L., B – *Matricaria recutita* L.

is already manifested in the germination phase, thanks to the realization of genetically–laid potential.

4. Conclusions

The study of seeds' salt hermesis of natural and cultural flora in the conditions of southern Ukraine showed that the number of days of germination (seeds of cultural flora germinates for 7–10 days, and in wild representatives this indicator is extended to 10–12 days) plants can be arranged in the following order: seven days – Secale cereal L., *Triticum durum* L., *Avena sativa* L., *Hordeum vulgare* L., *Helianthus annuus* L., *Matricaria recutita* L.; 10 days – *Beta vulgaris* L., *Phaseolus vulgaris* L. and 12 days – *Valeriana officinalis* L.

The aquatic environment is the most optimal for germination, but the numbers of sprouted seeds plants are in accordance with the list: *Helianthus annuus* L. → *Avena sativa* L. → *Triticum durum* L. → *Matricaria recutita* L. → *Secale cereale* L. → *Hordeum vulgare* L. → *Beta vulgaris* L. → *Valeriana officinalis* L. → Phaseolus vulgargaris L. → *Phaseolus vulgaris* L.

The study of seed stress tolerance demonstrated the differentiation of the influence of Na^+

and Cl^- ions (at a concentration of 0.1%) on physiological and biochemical processes, which led to the appropriate distribution of plants: *Triticum durum* L. → *Helianthus annuus* L. → *Hordeum vulgare* L. → *Matricaria recutita* L. → *Beta vulgaris* L. → *Valeriana officinalis* L. The concentration of 0.2% NaCl solution revealed the following sequence: Secale cereal L. → *Triticum durum* L. → *Helianthus annuus* L. → *Avena sativa* L. → *Matricaria recutita* L. → *Hordeum vulgare* L. → *Phaseolus vulgaris* L. → *Valeriana officinalis* L. → *Beta vulgaris* L.

The results obtained indicate that the chloride load in the seeds of plants manifests itself in the form of distress as well as eustress. It has been proved that the diagnostic features of chloride hermesis are more clearly manifested in the representatives of the cultural flora than the natural ones, which is caused by the implementation of the interrelation of the genetic program and phenotypic manifestations, which are related to the special climatic conditions of southern Ukraine (soil salinity, air and soil drought, etc.), which is of practical importance when developing strategies for growing crops on saline soils.

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References

[1] Chang C C and Turner B L 2019 *Journal of Ecology* **107**(2) 503–509 ISSN 00220477 URL https://doi.org/10.1111/1365-2745.13132
[2] Marcińska I, Czyczyło-Mysza I, Skrzypek E, Filek M, Grzesiak S, Grzesiak M T, Janowiak F, Hura T, Dziurka M, Dziurka K, Nowakowska A and Quarrie S A 2013 *Acta Physiologiae Plantarum* **35**(2) 451–461 ISSN 0137-5881 URL https://doi.org/10.1007/s11738-012-1088-6
[3] Ratajczak E, Staszak A M, Wojciechowska N, Bagniewska-Zadworna A and Dietz K J 2019 *Journal of Plant Physiology* **239** 61–70 ISSN 01761617 URL https://doi.org/10.1016/j.jplph.2019.06.002
[4] Giuffrida F, Graziani G, Fogliano V, Scuderi D, Romano D and Leonardi C 2014 *Journal of Plant Nutrition* **37**(9) 1455–1474 ISSN 0190-4167 URL https://doi.org/10.1080/01904167.2014.881874
[5] Pyurko O E, Velcheva L G and Arabadzhi-Tipenko L I 2022 *IOP Conference Series: Earth and Environmental Science* **1049**(1) 012071 ISSN 1755-1307 URL https://doi.org/10.1088/1755-1315/1049/1/012071
[6] Khrystova T Y, Musienko N N and Pyurko O E 2009 *Historical and methodological aspects of phytophysiological research in Ukraine* (Melitopol: Publishing House)
[7] Prach K and Walker L R 2019 *Journal of Ecology* **107**(2) 510–516 ISSN 00220477 URL https://doi.org/10.1111/1365-2745.13078
[8] Chaves M M, Flexas J and Pinheiro C 2009 *Annals of Botany* **103**(4) 551–560 ISSN 1095-8290 URL https://doi.org/10.1093/aob/mcn125
[9] Prudente D d O, Paiva R, Domiciano D, Souza L B d, Carpentier S, Swennen R, Silva L C, Nery F C, Máximo W P F and Panis B 2019 *Journal of Plant Physiology* **239** 71–82 ISSN 01761617 URL https://doi.org/10.1016/j.jplph.2019.05.014
[10] Kazakov Y O 2000 *Methodological bases of the experimentation on plant physiology* (Kyiv: Phytosociocenter)
[11] Franzisky B L, Geilfus C M, Kränzlein M, Zhang X and Zörb C 2019 *Journal of Plant Physiology* **236** 23–33 ISSN 01761617 URL https://doi.org/10.1016/j.jplph.2019.02.012
[12] Ali B, Pantha S, Acharya R, Ueda Y, Wu L B, Ashrafuzzaman M, Ishizaki T, Wissuwa M, Bulley S and Frei M 2019 *Journal of Plant Physiology* **240** 152998 ISSN 01761617 URL https://doi.org/10.1016/j.jplph.2019.152998
[13] Baghalian K, Haghiry A, Naghavi M R and Mohammadi A 2008 *Scientia Horticulturae* **116**(4) 437–441 ISSN 03044238 URL https://doi.org/10.1016/j.scienta.2008.02.014
[14] Zhang Y, Zhou Y, Chen S, Liu J, Fan K, Li Z, Liu Z and Lin W 2019 *Journal of Plant Physiology* **234–235** 145–153 ISSN 01761617 URL https://doi.org/10.1016/j.jplph.2019.02.007
[15] El Amrani A, Couée I, Berthomé R, Ramel F, Gouesbet G and Sulmon C 2019 *Journal of Plant Physiology* **238** 1–11 ISSN 01761617 URL https://doi.org/10.1016/j.jplph.2019.04.012
[16] Chrysargyris A, Solomou M, Petropoulos S A and Tzortzakis N 2019 *Journal of Plant Physiology* **232** 27–38 ISSN 01761617 URL https://doi.org/10.1016/j.jplph.2018.10.024

PAPER • **OPEN ACCESS**

Information provision for monitoring the sustainable development of the land and biodiversity

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Information provision for monitoring the sustainable development of the land and biodiversity

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Abstract. The study is focused on gathering information to monitor sustainable land development and biodiversity. The article discusses the objectives and measures required to achieve Sustainable Development Goal 15 "Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss". This paper shows the results of the analysis of key indicators and values for Ukraine. It also contains the developed conceptual diagram for managing the sustainable development of ecosystems and biodiversity. There were identified the main sources of statistical information, including traditional enterprise-level data and big data, and analyzed changes in indicators for monitoring the achievement of the Sustainable Development Goals at micro level under section "Environmental area". The study also identified potential sources of information for calculating the presented indicators and explored the use of big data to develop an information base for monitoring, evaluating, and policy development related to sustainable land development and biodiversity. Further research and studies are needed to determine the algorithms of data processing, modelling and constructing of integrated indicators.

1. Introduction

On September 25-27, 2015, the UN Summit was held in New York within the framework of the 70th session of the General Assembly of the United Nations. During the high-level meeting on sustainable development, 193 member states of the United Nations (UN) officially adopted a new program in the field of sustainable development, entitled "Transforming our world: The 2030 Agenda for Sustainable Development". The program officially entered into force on January 1, 2016 [1].

The term "sustainable development" was first used by the International Commission on Environment and Development in 1987 and was defined as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." The concept of sustainable development was adopted at the UN Conference on Development and Environment in Rio de Janeiro in 1992 [1].

To achieve sustainable development, it is extremely important to coordinate three main components – economic growth, social integration and environmental protection. These components are interconnected and extremely important for well-being of individuals and society as a whole. Therefore, sustainable development is defined as development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs.

UN member states have identified 17 sustainable development goals (SDGs) for the period up to 2030 and 169 tasks. These goals and objectives can be applied to any society. Achieving the SDGs requires all countries to integrate them into their national strategies and plans [1]. SDGs are not legally binding. It is assumed that governments of all countries take responsibility and create national mechanisms that will contribute to the achievement of the stated goals. In order to promote prosperity and protect the entire planet, the SDGs call for action by all countries without exception – poor, rich and middle-income countries. They are global in nature and universal in application, but at the same time take into account development specificities, national potential, as well as national strategies and priorities. Since they are interrelated, efforts to achieve them should be comprehensive.

At the global level, a set of indicators is used to monitor and review the process of implementing goals in the field of sustainable development and tasks of the new agenda [1]. Countries bear the primary responsibility for follow-up and review of progress in the implementation of goals, and for this it is necessary to ensure the collection of high-quality, accessible and relevant data.

Biodiversity is a key theme of the UN's 2030 Agenda for Sustainable Development which corresponds to SDG 14 and 15.

SDG 14 is dedicated to "Conserve and sustainably use the oceans, seas and marine resources".

SDG 15 is dedicated to "Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss".

2. Aim and methodology

Aspects of information provision of sustainable development were reflected in the works of Ukrainian statisticians [2].

Issues related to biodiversity monitoring, aspects of the importance of ensuring the long-term preservation of and access to data are considered in the works of Hardisty et al [3], Alblas and van Zeben [4], Alkemade et al [5], Navarro et al [6], Barral and Guillet [7], Moersberger et al [8], Schmeller et al [9], Schmidt et al [10], Blanco-Zaitegi et al [11], Brörken et al [12], Xie et al [13], Lu et al [14], Cipullo [15], Estoque et al [16], Ren et al [17], Tóth et al [18], Kong et al [19], Li and Lei [20], White et al [21], Spangenberg [22].

Study of Hardisty et al [3] is devoted to the issues of Essential Biodiversity Variables (EBV) – the fundamental variables that can be used for assessing biodiversity change over time, for determining adherence to biodiversity policy, for monitoring progress towards sustainable development goals, and for tracking biodiversity responses to disturbances and management interventions.

The research of Navarro et al [6] contributes to deepening of the understanding of coordinated observing system adopted by GEO BON, focusing on two interconnected core components – the Essential Biodiversity Variables as a standard framework for biodiversity monitoring, and the Biodiversity Observation Networks that support harmonized observation systems – while highlighting their societal relevance.

Moersberger et al [8] presented two key clusters of needs in Europe over the next 5-10 years: 1) biodiversity data are needed to ensure integrated cross-sectoral policies; 2) biodiversity data are needed to increase policy impact and effectiveness to fulfil goals of the EU Biodiversity Strategy.

Schmeller et al [9] presented a globally coordinated approach is needed for biodiversity monitoring that is linked to environmental data and covers all biogeographic regions. They identified nine requirements that they believe are necessary for developing and implementing such

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a global terrestrial species monitoring program: 1)designing and implementing an integrated information chain from monitoring to policy reporting; 2) capacity-building to create a comprehensive spatial monitoring program; 3) implementing minimal data standards to capture EBVs; 4) implementing common monitoring protocols; 5) developing and optimizing semantics and ontologies for data interoperability; 6) integrating emerging technologies (monitoring, data management and analysis); 7) coordinating diverse but complementary local nodes; 8) facilitating and securing funding.

Schmidt et al [10] reviewed different sampling strategies, methods of data collections and analysis according to the monitoring of habitat distribution, species population, species trends, etc.

Tóth et al [18] proposed frameworks of soil-related sustainable development goals and related indicators which can be monitored in current monitoring schemes.

Spangenberg [22] suggest simple ordinal scale index for monitoring of land use intensity changes. It is based on the hemeroby concept, measuring the human impact as deviation from naturalness. This makes it an information collection and presentation tool for those working in landscape planning and management.

Our research is devoted to information provision for monitoring the sustainable development of the land and biodiversity, which is primarily related to monitoring the achievement of the SDG 15.

Parties of the United Nations Convention on Biological Diversity are making efforts to ensure functioning of the global biodiversity conservation system for the period after 2020, the goal of which is to stabilize the loss of biodiversity by 2030 and fully restore natural ecosystems by 2050.

The purpose of sustainable development management ecosystems and biodiversity can be formulated as ensuring adaptability of society to preservation and improvement of the environment, responsible use of ecosystems and restoration of biodiversity.

3. Method

The use of statistical methods provides an opportunity to assess the level of achievement of the above-mentioned goal and outlines methods of accounting for aspects of sustainability.

Conceptual block diagram of information provision for the regulation of sustainable development of ecosystems and biodiversity which characterizes structure and sequence of operations aimed at justifying management decisions, is shown in figure 1.

A necessary condition for ensuring a systematic study of sustainable and responsible use of ecosystems and restoration of biodiversity is the formation of a single open database as an information source for ensuring management.

The content of analytical work consists of bringing disparate information to a logically constructed system of relationships, which makes it possible to give a reasonable assessment of both the entire set of facts and each of them separately, and to determine their role in solving the investigated problem.

The analysis of the dynamics of development components forms the basis of an objective assessment of the identification of trends and regularities.

The use of statistical methods makes it possible to translate many management problems into plane of accurate quantitative display with qualitative content, based on real information provision of calculations in accordance with user needs.

Appropriate software speeds up and improves information processing, significantly expanding the range of tasks that can be solved using statistical methods in the management process. This provides a creative approach to the performance of specific management tasks, the search for new ways to improve the quality and validity of management decisions, and the development of measures to improve efficiency in all areas of activity.

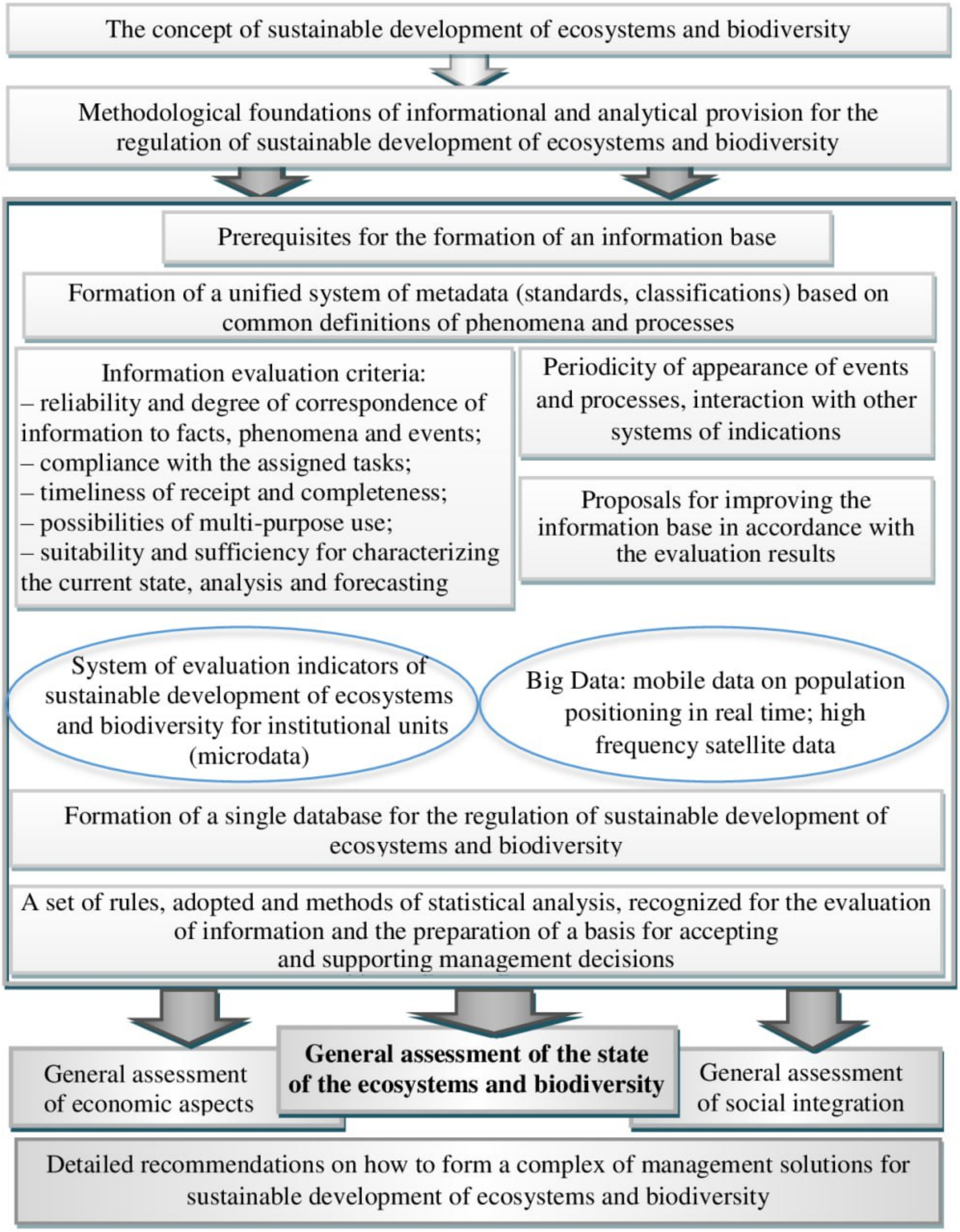

Figure 1. Conceptual block diagram of information provision for the regulation of sustainable development of ecosystems and biodiversity.

Statistical analysis should be used to determine the relationships between phenomena, the influence of the main factors on them, among which, in particular, those that arise as a result of the action of objective laws and cause the emergence of risks are distinguished. To do this, statistical models of various types of relationships are used – functional, stochastic, correlational.

On basis of the above directions of analysis, possibility of comprehensive usage of their results to reveal the mechanism of socio-economic phenomena and processes is determined. In particular, this refers to the economic efficiency of the information obtained based on the ratio of results and costs for obtaining it.

Based on the results of the statistical analysis, the main directions of management aimed at ensuring sustainable use of ecosystems and restoration of biodiversity are determined, taking into account objectively existing potential opportunities. At the same time, a list of tasks is formed, the sequence of their execution, methods of solving and mutual consistency of these tasks are determined. This creates a methodology for substantiating management decisions using statistical methods.

In this way, information provision of the system interconnection of target complex programs is formed: socio-economic, scientific-technical, digital, environmental, investment, regional, etc. in the system of ensuring sustainable use of ecosystems and restoration of biodiversity. It should be noted that in the process of developing and using information provision for sustainable development, it is necessary to use international standards, classifications and unified definitions (interpretations) of phenomena and processes that summarize modern world experience, as well as contribute to the prompt implementation of national analogues.

The problem of training modern specialists in statistics, who are able to perform the functions of analysts, experts and consultants in the field of management, is connected with the rapid development of the information society and the widespread introduction of information and communication technologies. Statisticians-analysts must be aware of availability of the necessary sources of statistical information in accordance with the formulated management tasks, systematize and classify it; apply the methods of its processing, generalization and drawing conclusions, as well as creatively use the obtained results of the analysis to prepare management decisions regarding sustainable local development and evaluate in real time the consequences of such management decisions.

4. Research results

4.1. Microdata

Company reporting is an important source of data for the Central Bank monitoring system. As the primary source of information on company performance, reporting can significantly improve SDGs monitoring mechanisms by providing stakeholders such as governments, investors and businessmen with instruments to assess the economic, environmental and social impact of companies on sustainable development. Accounting data for the formation of key indicators should be collected at the level of an institutional unit and aggregated by region.

Institutional units usually consist of several different units that produce different products/services and have different locations. In the system of national accounts, they are called establishments, and when tied to a certain territory – a local kind-of-activity units – LKAU [23]. This is especially true for large enterprises. The collection of data by individual institutions enables organizations with the necessary flexibility to meet a number of reporting requirements and facilitates compilation of environmental indicators.

For example, collection of data on environment at the level of individual objects will allow more detailed determination of areas of increased environmental danger. If an entity has facilities in different locations, it is likely that they operate under different conditions and have different environmental impacts. Therefore, it is useful to collect and compile environmental indicators for each facility first and then aggregate the reporting of institutional unit.

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Development of a unified list of main indicators for reporting by institutional units to ensure monitoring of SDGs achievement was initiated by UNCTAD (United Nations Conference on Trade and Development) in 2016 and extended in 2017 and 2018 [24]. In 2022, guidelines were issued on the definition and calculation of the main indicators for monitoring the achievement of the SDGs at the micro level [25].

The results of a detailed analysis of the changes in the indicators presented in the guide for 2016-2022 at the level of the group "Environmental area" are shown in figure 2.

Based on the results of case studies, discussions at the Advisory Group meeting and taking into account key international developments in this area, UNCTAD revised the main indicators of the SDGs. As a result, in 2022 minor changes were made to the measurement methodology and normalization of indicators, as well as clarification and elimination of inconsistencies. However, the main result was the addition of the main indicators of the SDGs with an indicator on land and biodiversity.

In the group of indicators "Ecology" of the micro level was added subgroup B.6 "Land and biodiversity", which includes indicator B.6.1 "Lands Used Near Biodiversity Sensitive Areas". This indicator is defined as the number and area (in hectares) of plots owned, leased or managed in protected areas and/or key biodiversity areas (KBA) or adjacent to them, i.e. those areas on the planet, which are critical to the survival of unique plants and animals, as well as ecological communities.

Indicator B.6.1 measured in accordance with the proposal set forth in [26]: "KBAs provide a science-based and internationally recognized means of identifying sites that make a significant contribution to global biodiversity conservation, while protected areas indicate nationally (and often internationally) recognized areas of ecological or cultural importance, typically with special legal protection. Conducting operations in or near such areas indicates an increased risk of adverse impacts on biodiversity and an increased risk of associated legal or reputational risk."

For reporting on this indicator B.6.1, the reporting entity must [25]:

- determine the location of surface and underground lands that may be owned, leased or managed by the organization;
- assess whether the land owned, leased or managed is located in protected areas/KBA and/or is adjacent to a protected area/KBA and/or contains parts of a protected area/KBA;
- determine amount and size of land owned, leased or managed, which is located in protected areas/KBA and/or is adjacent to a protected area/KBA and/or contains parts of a protected area/KBA, expressed in the number of hectares.

Among the potential sources of information, the following were identified.

(i) Information about the location of KBA (figure 3) can be found at [27].
As we can see that for Ukraine the information is presented for the year 2000.

(ii) Information on protected areas (figure 4) can be found by searching the global database at [28].

A number of events at the international level have changed format and framework of reporting on sustainable development. Attention should be paid to the fact that in November 2021 at the twenty-sixth Conference of the Parties within the framework of the UN Conference of the Parties on Climate Change [29] the International Sustainability Standards Board (ISSB) was announced. This new international body is engaged in the creation and development of international financial reporting standards related to sustainable development, which should become mandatory for institutional units in many countries of the world. Therefore, Ukraine should accelerate national efforts to create, establish or strengthen the technical capacity that will ensure compliance with the new reporting standards [30].

Sub-Area	Indicators 2016	Indicators 2022	Measurements (2022)	Relevant SDG indicator
B.1. Sustainable use of water		B.1.1: water recycling and reuse	Total volume of water recycled and/or reused by a reporting entity during the reporting period in absolute amount and in % terms	6.3.1
	B.1: water consumption per net value added	B.1.2: water use efficiency	Net value added divided by the water use in the reporting period as well as change of net value added divided by the change of water use between two reporting periods	6.4.1
		B.1.3: water stress	Water withdrawn with a breakdown by sources and with reference to water-stressed or water-scarce areas in absolute amount and in % terms	6.4.2
B.2. Waste management		B. 2.1: waste generation	Change in the entity's waste generation per net value added in % terms, in terms of change and in absolute amount	12.5
	B.2: waste generated per net value added	B.2.2: waste reused, remanufactured and recycled	Total amount of waste reused, remanufactured and recycled in absolute amount, in % terms and in terms of change	12.5.1
		B.2.3: hazardous waste generation	Total amount of hazardous waste, in absolute terms, as well as proportion of hazardous waste treated, given total waste reported by the reporting entity	12.4.2
B.3. Greenhouse gas emissions	B.3: greenhouse gas emissions (scopes 1–2) per net value added	B.3.1: greenhouse gas emissions (scope 1)	Scope 1 contribution in absolute amount, in % terms and in terms of change	9.4.1
		B.3.2: greenhouse gas emissions (scopes 2)	Scope 2 contribution in absolute amount, in % terms and in terms of change	9.4.1
B.4. Chemicals, including pesticides and ozone-depleting substances		B.4.1: ozone-depleting substances and chemicals dependency	Total amount of ozone-depleting substances (ODS) (bulk chemicals/substances existing either as a pure substance or as a mixture) per net value added.	12.4.2
B.5. Energy consumption		B.5.1: share of renewable energy	Renewable energy consumption as percentage of total energy consumption in the reporting period	7.2.1
	B.5: energy consumption per net value added	B.5.2: energy efficiency	Energy consumption per net value added	7.3.1
B.6. Biodiversity		B.6.1: land use adjacent to biodiversity sensitive areas	Number and area (in hectares) of sites owned, leased or managed in or adjacent to protected areas and/or key biodiversity areas	

Figure 2. Core Sustainable Development Goal Indicators: Environmental area.

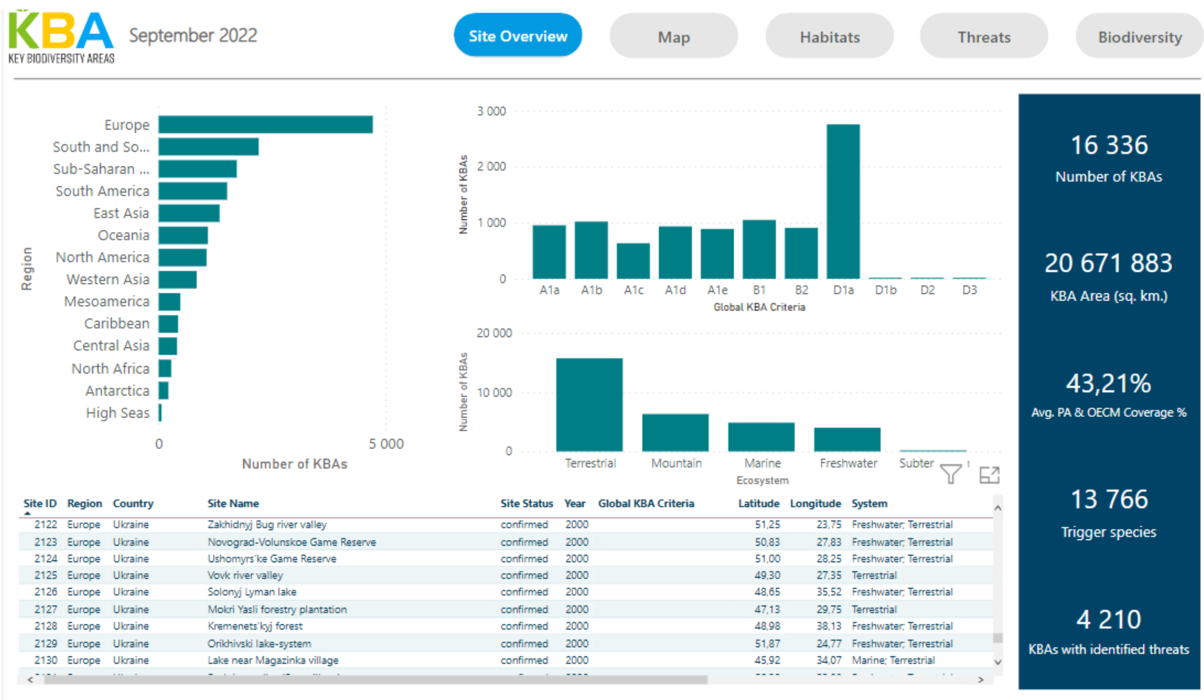

Figure 3. Key Biodiversity Areas (KBA) database.

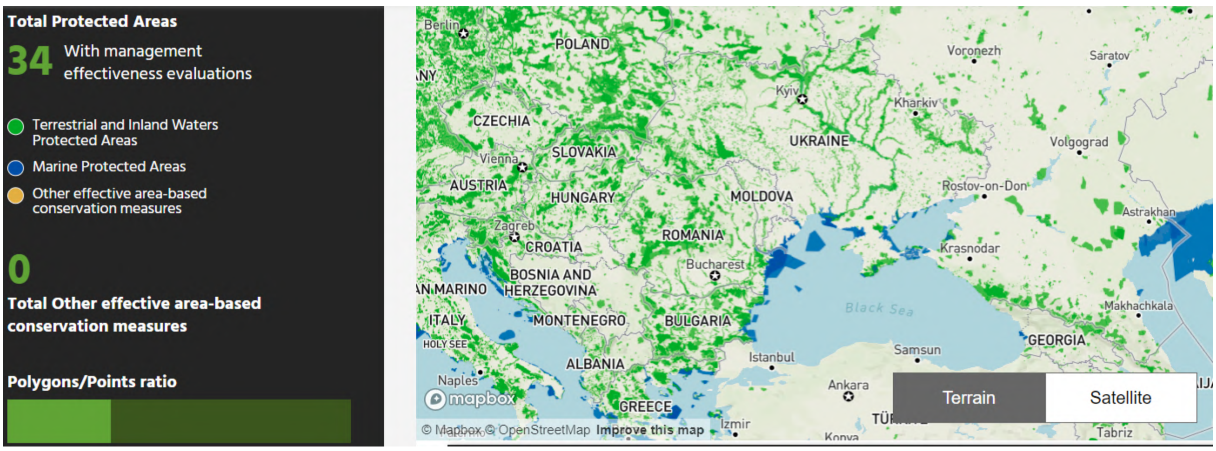

Figure 4. Protected areas from the Protected Planet global database.

Recent world events have reinforced the need for guidelines to support policymakers in building a robust national sustainability reporting infrastructure. This would ensure high quality reporting and support the implementation of future ISSB standards. All of the above confirms the relevance and importance of transparent measurement and disclosure, as well as comparability and reliability of information on sustainable development.

But it should be taken into account that placing an excessive burden on institutional units may harm the involvement of the private sector in obtaining quality information necessary to monitor the achievement of the SDGs. Therefore, it is recommended to apply a step-by-step approach, according to which, for the selected indicators, first the problems that the institutional unit controls and for which it collects relevant data are identified, or situations in which the company has unimpeded access to relevant sources of information.

4.2. Big data

The emergence of “big” data is closely related to the development of information and communication technologies. In today’s hyper-connected digital world, people and things leave “digital footprints” in many different forms, creating ever-increasing streams of data, including commercial transactions, private and public records that companies and governments collect and store, created by users online materials such as photos, videos, tweets and other messages, as well as traces left by the Internet of Things (IoT), i.e. those uniquely identifiable objects that can be tracked.

There is no single, unique definition of this relatively new phenomenon known as “big data”. At the most basic level, big data refers to data sets whose volume, velocity, or diversity are very high compared to the types of data sets that have traditionally been used. It is appropriate to refer to such definitions of the essence of this concept, with which most scientists agree. The first definition was proposed by Marv Adrian in 2011 in an article for Teradata Magazine: “Big data is data that cannot be collected, managed and processed with the help of the most commonly used hardware environments and software tools within the time allowed by the user” [31].

The data revolution, which includes the open data movement, new ICTs for data collection and the availability of big data, together with the emergence of artificial intelligence and the Internet of Things, has led to a radical transformation of society. Recently, “big data” began to be processed and analyzed in order to find relationships in economic and social systems, which was previously carried out with the help of surveys, experiments and other types of data collection, on the basis of which solutions were developed and forecasts were built.

Real-time mobile population positioning data and high-frequency satellite data are just main examples of big data that can be used to monitor the achievement of SDG 15.

Fixed and mobile telecommunications network operators, including Internet service providers, are an important source of data, and all forms of telecommunications big data (volume, speed or diversity) are considered for analysis purposes. Most telecommunications data can be considered as the result of an action (for example, making a call, sending an SMS, accessing the Internet or recharging a prepaid card).

An example of how mobile network data can track population movements is the 2010 Haiti earthquake. Figure 5 shows the number of people estimated to be in Port-au-Prince (PaP) on the day of the 2010 Haiti earthquake and outside the capital 19 days later [31].

One of the main projects aimed at integrating the development of big data for monitoring, evaluation and policy development within Group on Earth Observations Biodiversity Observation Network (GEO BON) is UN Biodiversity Lab [32], a geospatial information platform that maps natural resources and monitors environmental risks in real time using existing data and new digital technologies.

As part of the above-mentioned project, in 2022 the calculated data sets and indicators were included in the existing decision support system based on the UN Biodiversity Laboratory. Project data and indicators will be regularly updated until 2030 through the UN Biodiversity Lab [32]. The project is also a demonstration of the Observations for Sustainable Development Goals initiative [33]. The results of the project are expected to provide modern digital foundation for scaling up this forecasting methodology to more countries around the world working to monitor progress towards SDG 15. The project envisages widespread use in 170 UNDP partner countries of datasets, a brief the characteristics of which are presented in figure 6.

Within the framework of this study, the available statistical data on the considered data sets, included in the existing decision support system, using the electronic database of the UN Biodiversity Lab [32]. Below, for example, the results for several main blocks are presented.

Global Forest Change. Many organizations deal with forest change issues, so the

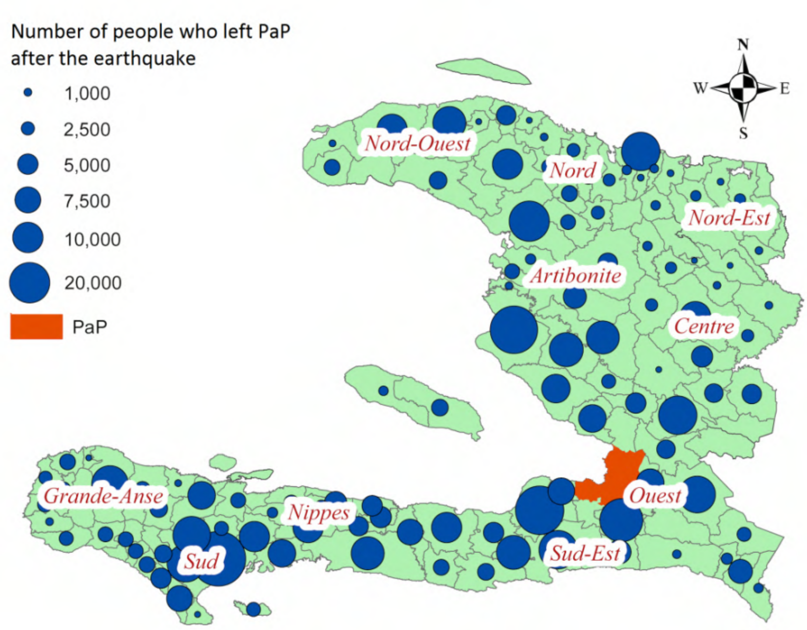

Figure 5. Tracking the mobility of the population in emergency situations using mobile phones (circles are shown for communes that received at least 500 persons).

definitions related to this concept are important and should be unified during the information provision of the study. Below are the definitions used by the FAO Forestry Department:

- Forests are lands of more than 0.5 hectares, with a tree canopy cover of more than 10 percent, which are not primarily under agricultural or urban land use.
- “Deforestation” is conversion of forest to another land use or long-term reduction of tree canopy cover below the 10% threshold.
- “Afforestation” is the conversion from other land uses into forest, or the increase of the canopy cover above the 10% threshold.
- “Reforestation” is re-establishment of forest formations after a temporary condition with less than 10% canopy cover due to human-induced or natural disturbances.
- “Forest degradation” is a reduction of the canopy cover or stocking within a forest.
- “Forest improvement” is the increase of the canopy cover or stocking within a forest.

Figure 7 shows changes in forest cover in Ukraine for 2001–2020.

Over the past twenty years (2001–2020), Ukraine lost 10.8 thousand square km, which was 1.8% of the forest cover in 2000.

Biodiversity Intactness Index. Biodiversity intactness index reflects the results of modeling the average number of originally present biological species, expressed as a percentage of their total number in a pristine ecosystem. Initially, the data was only available for 2015, but is now available in a time series covering the period 2000-2015.

Figure 8 shows value of the index for Ukraine in 2015.

Enhanced Vegetation Index (EVI). The Extended Vegetation Index (EVI) reflects the state of the vegetation during one year. High values of this index (closest to 1) represent dense and stably productive vegetation. Conversely, low values (close to 0) represent sparse vegetation with low productivity.

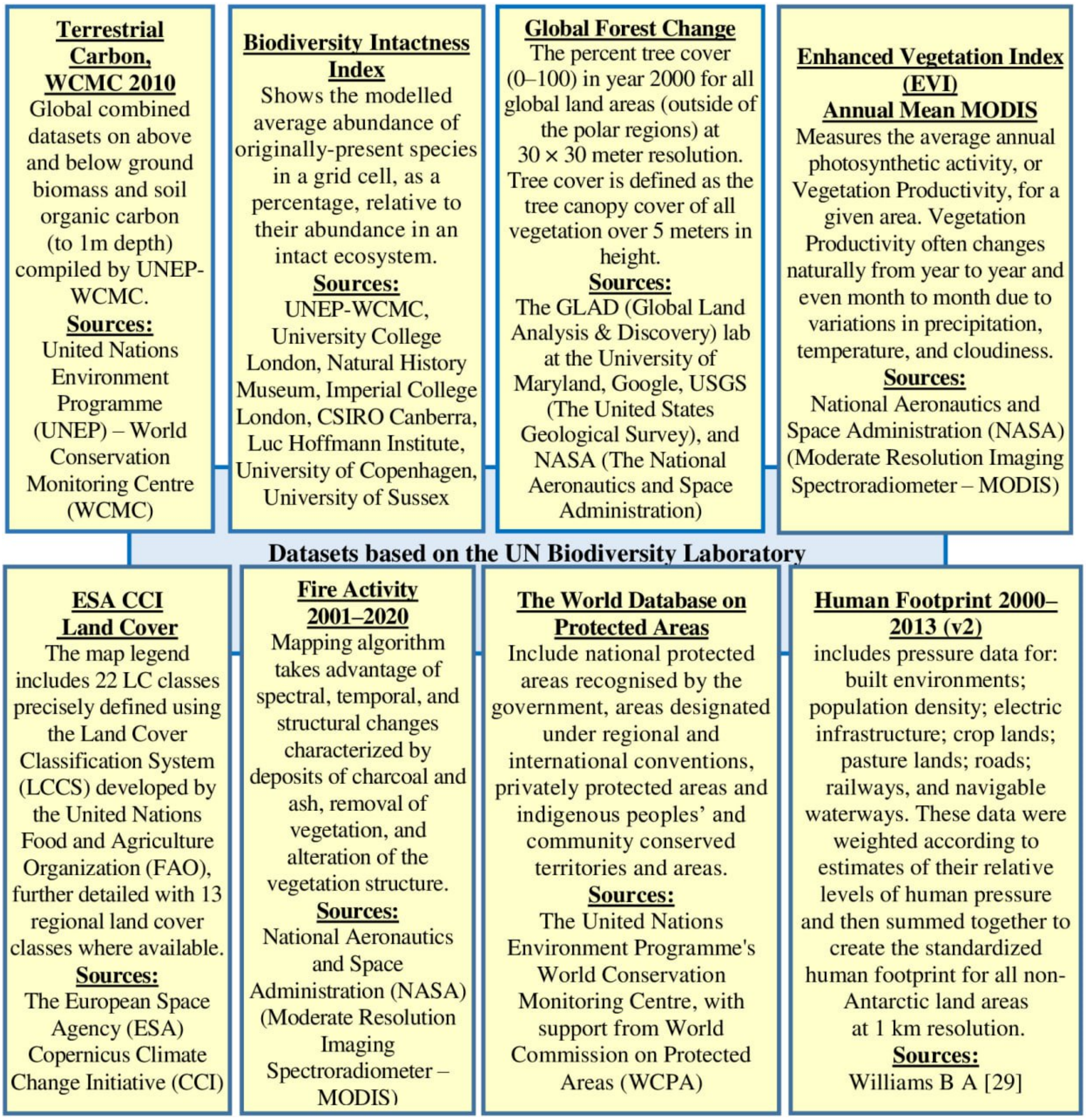

Figure 6. Datasets, included in the existing decision support system based on the UN Biodiversity Laboratory.

Average annual EVI values characterize the average annual photosynthetic activity, or vegetation productivity, for a certain area.

Vegetation productivity often varies naturally from year to year and even from month to month due to fluctuations in precipitation, temperature, and cloudiness.

With long-term observations, such assessments allow inferences about abnormal conditions, such as changes in land use or drought.

Figure 9 shows changes of Enhanced Vegetation Index in Ukraine in 2000-2021.

ESA CCI Land Cover. The European Space Agency and Copernicus Climate Change produced global land cover (LC) maps from 1992 to 2020 at 0.002778° (approximately 300 m)

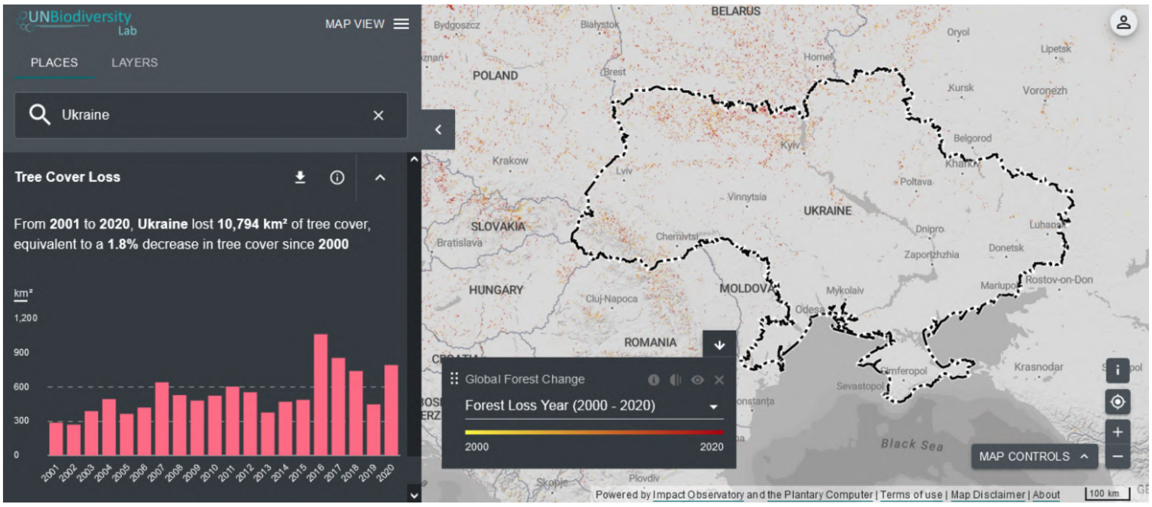

Figure 7. Forest change in Ukraine in 2001–2020.

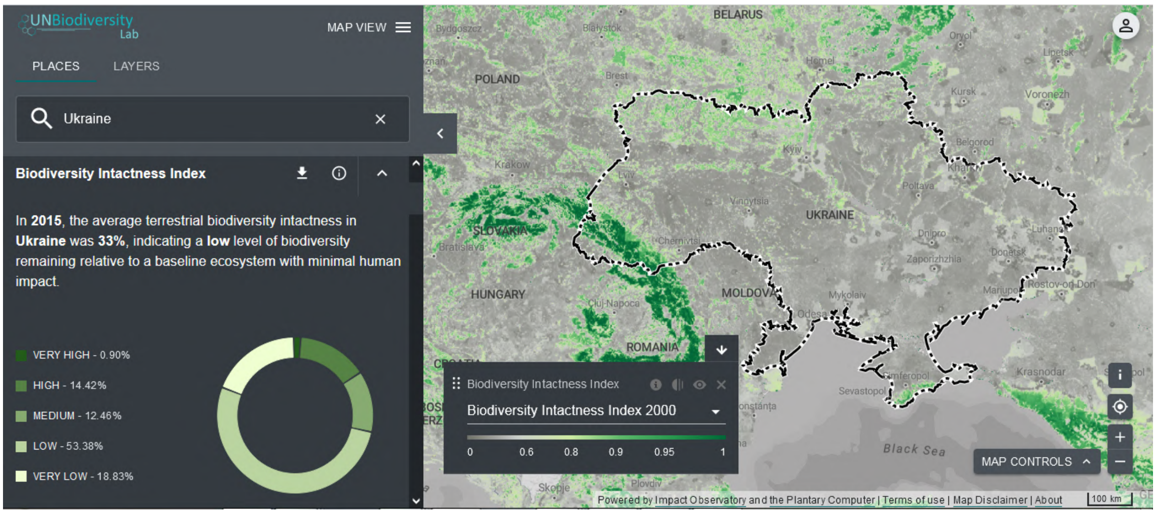

Figure 8. Biodiversity Intactness Index in Ukraine in 2015.

from the complete 300 m and 1 km multi-mission Earth observation (EO) archives. The map legend contains 22 LC classes that are precisely defined using the Land Cover Classification System (LCCS) developed by the Food and Agriculture Organization of the United Nations (FAO). 13 regional soil cover classes are detailed.

Figure 10 shows Ukraine's Land Cover in 2020.

Methodological decoupling of LC classification and LC change detection (LCC) ensures temporal and spatial consistency between successive maps. A new land cover map is created every year 9 months after the start of the year and is reviewed within a maximum of 3 months after publication. A user tool was developed to convert the LCCS nomenclature into plant functional type distributions used in various climate models.

5. Conclusions

Information provision for monitoring the sustainable development of land and biodiversity should be based on an understanding of the integrated use of statistical, administrative data sources,

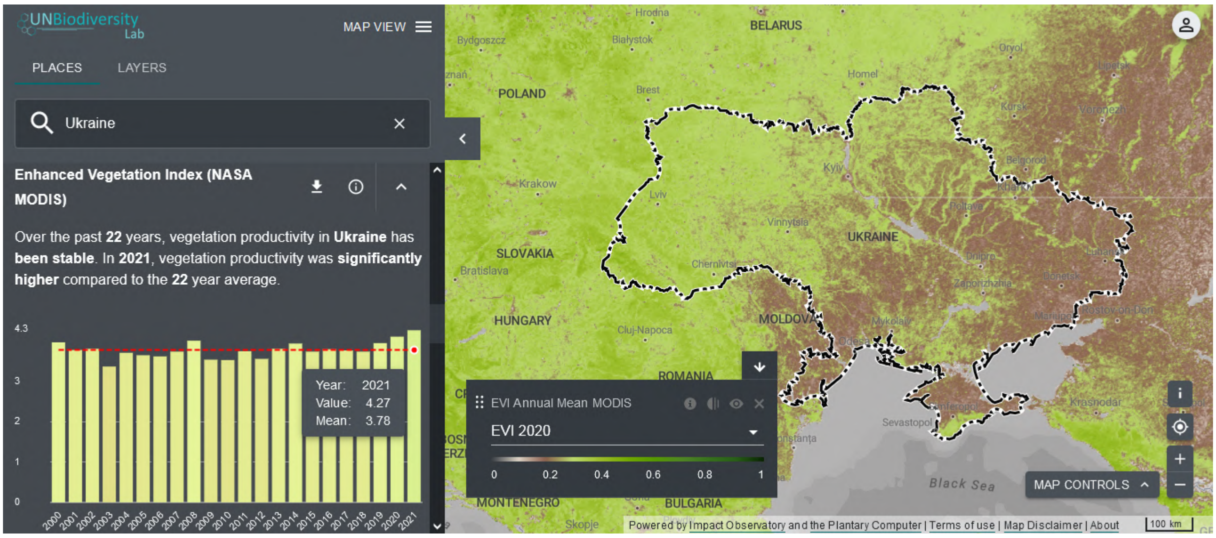

Figure 9. Enhanced Vegetation Index (NASA MODIS) in Ukraine in 2000-2021.

Figure 10. Ukraine's Land Cover in 2020.

metadata for their qualitative use, as well as a combination with big data, such as satellite images and data from mobile operators.

Recently, special attention should be paid to the collection of information on impacts on biodiversity in a specific place. Understanding the local context where an organization interacts with biodiversity is necessary to assess its impact, as well as to identify key drivers of biodiversity loss (overexploitation of resources, pollution, land-use change and climate change, etc.). It is also necessary to develop a program of actions that the organization needs to take to manage its impact on biodiversity.

Advances in computing and data science make it possible to process and analyze big data in real time. Integrating big data with traditional data should yield high-quality information that is more detailed, timely, and relevant. New insights derived from such data analysis can complement official statistics and survey data, adding depth and nuance to information in the course of monitoring the achievement of the Sustainable Development Goals.

Analysis of relevant trends over the long term can help maximize efforts to ensure sustainable land development and biodiversity conservation, and minimize environmental degradation and other potential negative consequences of increasing human impact on ecosystems.

The algorithms of data processing, modelling and constructing of integrated indicators would be the future research subject.

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References

[1] United Nations Take Action for the Sustainable Development Goals - United Nations Sustainable Development URL https://www.un.org/sustainabledevelopment/sustainable-development-goals/
[2] Zahozhai V B, Lazebnyk I O and Chala T G 2018 *Business Inform* (6) 208–214 URL https://www.business-inform.net/export_pdf/business-inform-2018-6_0-pages-208_214.pdf
[3] Hardisty A R, Michener W K, Agosti D, Alonso García E, Bastin L, Belbin L, Bowser A, Buttigieg P L, Canhos D A, Egloff W, De Giovanni R, Figueira R, Groom Q, Guralnick R P, Hobern D, Hugo W, Koureas D, Ji L, Los W, Manuel J, Manset D, Poelen J, Saarenmaa H, Schigel D, Uhlir P F and Kissling W D 2019 *Ecological Informatics* **49** 22–31 ISSN 1574-9541 URL https://doi.org/10.1016/j.ecoinf.2018.11.003
[4] Alblas E and van Zeben J 2023 *Land Use Policy* **127** 106577 ISSN 0264-8377 URL https://doi.org/10.1016/j.landusepol.2023.106577
[5] Alkemade R, van Bussel L G, Rodríguez S L and Schipper A M 2022 *Current Opinion in Environmental Sustainability* **56** 101174 ISSN 1877-3435 URL https://doi.org/10.1016/j.cosust.2022.101174
[6] Navarro L M, Fernández N, Guerra C, Guralnick R, Kissling W D, Londoño M C, Muller-Karger F, Turak E, Balvanera P, Costello M J, Delavaud A, El Serafy G, Ferrier S, Geijzendorffer I, Geller G N, Jetz W, Kim E S, Kim H, Martin C S, McGeoch M A, Mwampamba T H, Nel J L, Nicholson E, Pettorelli N, Schaepman M E, Skidmore A, Sousa Pinto I, Vergara S, Vihervaara P, Xu H, Yahara T, Gill M and Pereira H M 2017 *Current Opinion in Environmental Sustainability* **29** 158–169 ISSN 1877-3435 URL https://doi.org/10.1016/j.cosust.2018.02.005
[7] Barral S and Guillet F 2023 *Land Use Policy* **127** 106545 ISSN 0264-8377 URL https://doi.org/10.1016/j.landusepol.2023.106545
[8] Moersberger H, Martin J G C, Junker J, Georgieva I, Bauer S, Beja P, Breeze T, Brotons L, Bruelheide H, Fernández N, Fernandez M, Jandt U, Langer C, Solheim A L, Maes J, Moreira F, Pe'er G, Santana J, Shamoun-Baranes J, Smets B, Valdez J, McCallum I, Pereira H M and Bonn A 2022 *ARPHA Preprints* **3** URL https://doi.org/10.3897/arphapreprints.e84517
[9] Schmeller D S, Julliard R, Bellingham P J, Böhm M, Brummitt N, Chiarucci A, Couvet D, Elmendorf S, Forsyth D M, Moreno J G, Gregory R D, Magnusson W E, Martin L J, McGeoch M A, Mihoub J B, Pereira H M, Proença V, van Swaay C A, Yahara T and Belnap J 2015 *Journal for Nature Conservation* **25** 51–57 ISSN 1617-1381 URL https://doi.org/10.1016/j.jnc.2015.03.003
[10] Schmidt A M, van der Sluis T, van Swaay C, Mücher C A, Hazeu G W, Henkens R J H G, Verweij P J F M, Decleer K, Bijlsma R J and Jongman R H G 2021 *Improving the availability of data and information on species, habitats and sites: Focus Area A, Guidance on the application of existing scientific approaches, methods, tools and knowledge for a better implementation of the Birds and Habitat Directives* (European Commission) URL https://webcache.googleusercontent.com/search?q=cache:4DGsJvjKTUEJ:https://www.ecologic.eu/sites/default/files/publication/2021/A_EBind_Handbook.pdf&cd=9&hl=en&ct=clnk&gl=ua&client=ubuntu
[11] Blanco-Zaitegi G, Álvarez Etxeberria I and Moneva J M 2022 *Journal of Cleaner Production* **371** 133677 ISSN 0959-6526 URL https://doi.org/10.1016/j.jclepro.2022.133677
[12] Brörken C, Hugé J, Dahdouh-Guebas F, Waas T, Rochette A J and de Bisthoven L J 2022 *Environmental Science & Policy* **136** 114–126 ISSN 1462-9011 URL https://doi.org/10.1016/j.envsci.2022.05.017
[13] Xie L, Bulkeley H and Tozer L 2022 *Environmental Science & Policy* **132** 119–130 ISSN 1462-9011 URL https://doi.org/10.1016/j.envsci.2022.02.017

[14] Lu L, Qureshi S, Li Q, Chen F and Shu L 2022 *Ocean & Coastal Management* **224** 106201 ISSN 0964-5691 URL https://doi.org/10.1016/j.ocecoaman.2022.106201
[15] Cipullo N 2016 *Procedia Economics and Finance* **39** 539–544 ISSN 2212-5671 3rd GLOBAL CONFERENCE on BUSINESS, ECONOMICS, MANAGEMENT and TOURISM URL https://doi.org/10.1016/S2212-5671(16)30297-0
[16] Estoque R C, Ooba M, Togawa T, Hijioka Y and Murayama Y 2021 *Habitat International* **115** 102403 ISSN 0197-3975 URL https://doi.org/10.1016/j.habitatint.2021.102403
[17] Ren Q, He C, Huang Q, Zhang D, Shi P and Lu W 2023 *Resources, Conservation and Recycling* **190** 106834 ISSN 0921-3449 URL https://doi.org/10.1016/j.resconrec.2022.106834
[18] Tóth G, Hermann T, da Silva M R and Montanarella L 2018 *Environmental Monitoring and Assessment* **190**(2) 57 ISSN 1573-2959 URL https://doi.org/10.1007/s10661-017-6415-3
[19] Kong X, Zhou Z and Jiao L 2021 *Resources, Conservation and Recycling* **174** 105770 ISSN 0921-3449 URL https://doi.org/10.1016/j.resconrec.2021.105770
[20] Li X and Lei L 2023 *Regional Sustainability* **4**(1) 96–114 ISSN 2666-660X URL https://doi.org/10.1016/j.regsus.2023.03.002
[21] White T B, Mukherjee N, Petrovan S O and Sutherland W J 2023 *Environmental Science & Policy* **140** 221–231 ISSN 1462-9011 URL https://doi.org/10.1016/j.envsci.2022.12.003
[22] Spangenberg J H 2023 *Land* **12**(4) 820 ISSN 2073-445X URL https://doi.org/10.3390/land12040820
[23] European Communities, International Monetary Fund, Organisation for Economic Co-operation and Development, United Nations and World Bank 2009 *System of National Accounts 2008)* (New York) URL https://unstats.un.org/unsd/nationalaccount/docs/SNA2008.pdf
[24] 2016 Enhancing the role of reporting in attaining the Sustainable Development Goals: Integration of environmental, social and governance information into company reporting URL https://unctad.org/meetings/en/SessionalDocuments/ciiisard78_en.pdf
[25] United Nations 2022 *Guidance on Core Indicators for Sustainability and SDG Impact Reporting* (New York) URL https://unctad.org/system/files/official-document/diae2022d1_en.pdf
[26] 2020 Measuring Stakeholder Capitalism: Towards Common Metrics and Consistent Reporting of Sustainable Value Creation White paper World Economic Forum Cologny/Geneva URL https://www3.weforum.org/docs/WEF_IBC_Measuring_Stakeholder_Capitalism_Report_2020.pdf
[27] 2023 KBA Data URL http://www.keybiodiversityareas.org/kba-data
[28] Protected Planet 2023 Explore the World's Protected Areas URL https://www.protectedplanet.net/en
[29] 2023 Delivering the Glasgow Climate Pact URL https://webarchive.nationalarchives.gov.uk/ukgwa/20230401054904/https://ukcop26.org/
[30] 2022 GRI Topic Standard Project for Biodiversity – Exposure draft URL https://www.globalreporting.org/media/yuefwx4e/item-01-gri-topic-standard-project-for-biodiversity-exposure-draft.pdf
[31] Korepanov O S 2018 *Agrosvit* (8) 56–61 URL https://www.agrosvit.info/pdf/12_2018/10.pdf
[32] UN Biodiversity Lab 2023 Providing decision makers with the best available spatial data to put nature at the center of sustainable development URL https://unbiodiversitylab.org
[33] EO4SDG Team 2019 Earth observations for sustainable development goals: Strategic implementation plan URL https://www.earthobservations.org/documents/gwp20_22/eo_for_sustainable_development_goals_ip.pdf

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A system of environmentally important decision-making for the sustainable use of marine estuaries in the conditions of anthropogenic and climatic changes

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A system of environmentally important decision-making for the sustainable use of marine estuaries in the conditions of anthropogenic and climatic changes

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Abstract. Sustainable use of marine water areas is one of the priorities of preserving biodiversity and the environment as a whole. The problem of a clear plan of rehabilitation measures, which would be based on complex and balanced solutions arises for their effective restoration and further functioning. These decisions should take both environmental and economic aspects into account. Estuaries, unlike marine water areas, are more sensitive to anthropogenic and climatic changes. They are characterized by shallow water level, functioning in the conditions of limited water exchange, dependence on river flow and greater anthropogenic load compared to marine water areas. These features are the cause of more intensive changes in the structure of biocenoses, rise in emergency situations, loss of productivity and sustainability of ecosystems as a whole. Thus, there is a need to introduce environmental management for these reservoirs, which should be based on a multi-component decision support system. This system will make it possible to develop clear plans for the restoration of marine ecosystems and prevent negative changes and degradation in them. The proposed scheme for developing plans for the restoration of the ecosystems of estuaries is represented by three blocks. The first "Block of data collection" involves the implementation of 3 stages: assessment of the current state of the reservoir; definition of problems and their ranking; assessment of ecosystem services. The second block "Search for a solution" is based on 4 components: Component 1. Database management system; Component 2. Geoinformational system; Component 3. Mathematical and predictive models; Component 4. Informational and management system for choosing strategic and operational decisions. The third block "Implementation of measures" involves the implementation of 4 stages: environmental assessment of decisions and projects, implementation of environmental measures, evaluation of effectiveness, search for new solutions and their improvement. The proposed scheme will enable a comprehensive approach to the restoration of estuarine ecosystems and ensure their sustainable use.

1. Introduction

The United Nations has declared 2021–2030 as the International Decade on Ecosystem Restoration. The goal of this decade is to bring together all interested parties to prevent, halt and reverse the degradation of ecosystems on every continent and in every ocean. This initiative provides many areas of work that will draw attention to the problems of restoring ecosystems and ensure their sustainable use in the future [1].

The experience of European countries in the management of ecotones, lagoons and estuaries is quite broad and has several main directions. All of them are based on the basic principles of the role of water bodies as ecosystems that provide many ecological, cultural and economic benefits and advantages for people.

Most approaches to the estuary management are based on the implementation of clear measures to optimize the hydrological regime, reduce the anthropogenic load, protect certain biotopes or species, educational measures, etc. [2–6].

In general, most countries are trying to systematically solve the problems of managing coastal and marine ecosystems both at the legislative level and at the sectoral level (fisheries, recreation, nature protection). This approach involves giving a certain status to the water body and subsequently developing a clear management plan that depends on the specifics of the ecosystem use.

Unfortunately, in Ukraine, approaches to the systematic management of the water bodies are not carried out. Plans for the management of individual river basins are only partially implemented [7–9]. This work is carried out within the framework of the implementation of the approaches of the EU Water Framework Directive implemented by Ukraine. For estuaries, separate attempts to develop management plans were carried out exclusively within the framework of management plan development for wetlands of international importance or touched on the management of hydrological or hydrochemical regimes [10].

Unfortunately, marine ecosystems, especially the coastal ones, have been significantly transformed over the past 50–60 years due to pollution, construction of industrial facilities, intensive development of recreation, et cetera. The speed of negative developments was intensified by the impact of threatening climate changes, which have also intensified in recent years. Estuaries are especially sensitive in this context since they, unlike marine water areas, are shallower, function with limited water exchange, depend on river flow and are characterized by a greater anthropogenic load.

From a scientific point of view, these water bodies are important for the possibility of control and implementation of various management measures to regulate and restore hydrological, hydrochemical and hydrobiological regimes. The possibility of introducing active measures aimed at stabilizing and improving ecological processes is an important condition for restoring transformed ecosystems to their natural state [11] .

For a long time, the management of these water bodies took place spontaneously and was aimed at the formation of various ecological states. Most of the feasible anthropogenic transformations have changed the course of natural processes in these ecosystems. Some ecosystems were radically transformed, isolated from sea waters, changed both at the level of abiotic characteristics and at biocenosis level [12–16].

That is why we propose a systematic approach to the environmental management process, the main element of which should be a multi-component decision support system. This scheme will enable to develop clear plans for the restoration and sustainable use of marine ecosystems, as well as to prevent negative changes and degradation of marine water areas.

2. Results and discussion

Despite the obvious need to develop a systematic approach to decision support in estuary management, there are currently no complete step-by-step schemes that allow for a comprehensive solution to the tasks of ecological management. The main defects and problems of modern ecological solutions implemented in Ukraine are:

- lack of systematic scientific studies of the state of water bodies, which should be implemented on the basis of the basin approach and the requirements of the Water Framework Directive;

- lack of works on the assessment of ecosystem services as a tool for understanding the ecological, social and resource value of water areas;
- insufficient use of elements of the mathematical modelling of hydroecological and socio-economic processes;
- lack of understanding of the need to involve experts of appropriate qualifications by the customers and their reluctance to finance the full scope of the development at the design stage;

Taking the lack of systemic solutions in the management of estuaries into account, there is a need to develop a complete step-by-step scheme that will allow to comprehensively solve the problems of ecological management. Water body management has long gone beyond purely ecological problems and today should be based on a combination of not only ecological indicators and criteria, but also include social, economic, political and legal instruments. In general, the functioning of this scheme should be based on a number of principles:

- *The principle of a holistic approach towards assessing the state of aquatic ecosystems.* It involves a comprehensive assessment of the body of water and the factors affecting it. It is important to analyse all key factors that determine the ecological state of the body of water, and not the individual components.
- *The principle of the basin approach.* The approach assumes that the drainage basin together with the body of water forms a single geoecosystem with transit and accumulative functions and directly affects the formation of the ecological status-class of hydroecosystems.
- *The principle of sustainable development.* Sustainable development is considered as a compromise between economic, environmental and social spheres. The concept of sustainable development is based on three main principles [14]:
  - ensuring a balanced economy and ecology;
  - ensuring the balance of the economic and social spheres in the human dimension, which means the maximum use of the resources provided by economic development in the interests of the population;
  - solving tasks related to development not only in the interests of the current generation, but also of all subsequent generations that have equal rights to resources.

The proposed scheme has three blocks: a data collection block, solution search block, and a measure implementation block (figure 1). These blocks are sequential and must be implemented in stages.

Stage 1. Assessment of the current state of the body of water. This stage is associated with the need to conduct complex hydroecological studies. It is important to note that in Ukraine on September 19, 2020, the Resolution of the Cabinet of Ministers of Ukraine approved the Procedure for State Water Monitoring. State water monitoring is carried out in order to ensure the collection, processing, preservation, generalization and analysis of information about the state of the bodies of water, forecasting its changes and developing scientifically based recommendations for decision support in the field of water use, protection and reproduction of water resources. It is important to note that this monitoring is based on the basin principle and is regulated by the EU Water Framework Directive. Today, unfortunately, the water monitoring system is not fully implemented. Modern works performed by authorized bodies relate to the formation of reference indicators. At the same time, the assessment is based on the comparison of the current values of hydrobiological, physicochemical and hydromorphological indicators, determined in the monitoring process, with their reference values, that is, those that could exist in the absence of anthropogenic influence [15].

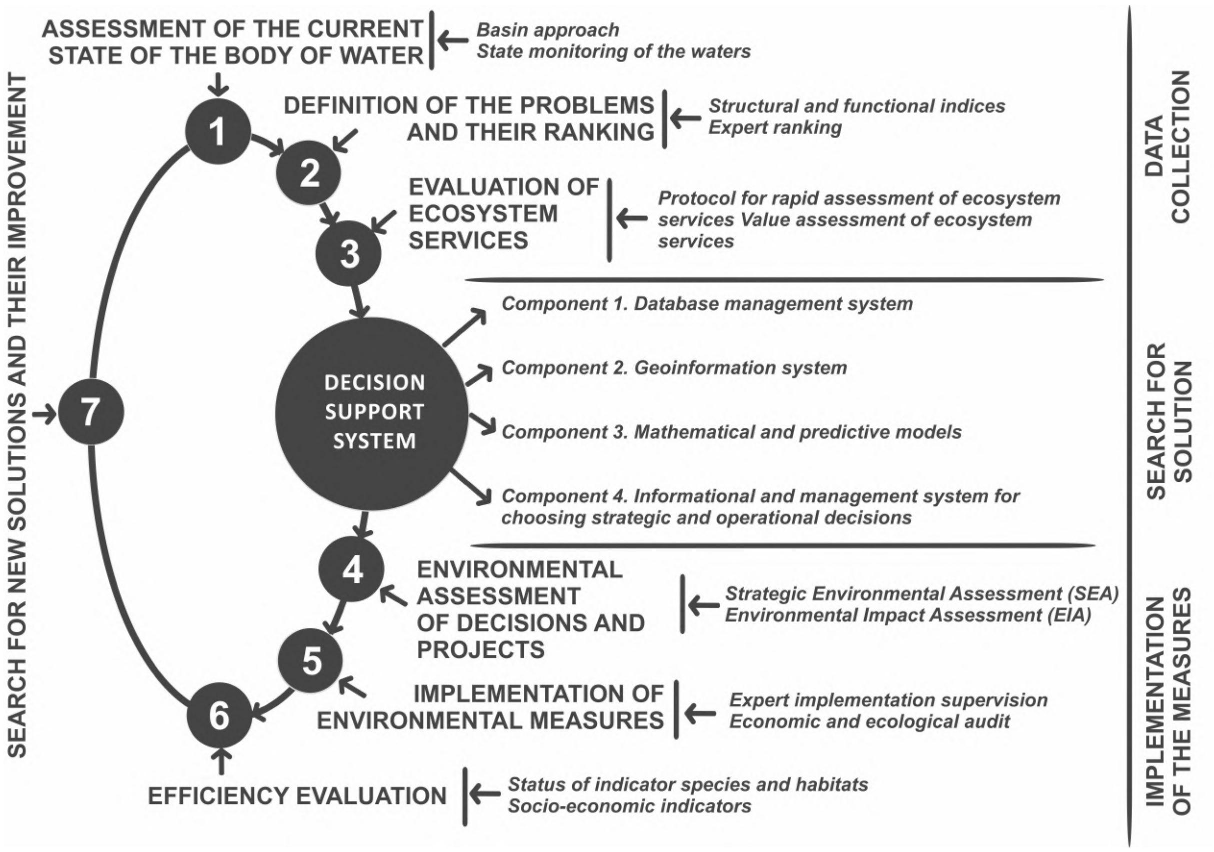

Figure 1. Scheme of the stages of making systemic decisions on estuary management

Stage 2. Definition of the problems and their ranking. Work in this stage involves the use of integrated structural and functional indicators that allow assessing problems in the ecological state of estuaries or the imperfection of management decisions. At the same time, there are cases when it is necessary to give prospective assessments to qualitatively new processes and phenomena that have not been encountered before and about which, of course, there is no information. The possibility of solving the mentioned problems, even in the absence of theoretical justifications, is achieved due to the skilful use of experience, intuition and knowledge of specialists, scientists working on solving the relevant problems. This method is called the method of expert evaluations [16]. It allows to rank ecological problems and to determine environmental management priorities. According to the results of this stage, priority problems will be determined, the solution of which will have the greatest cumulative effect.

Stage 3. Evaluation of ecosystem services. Ecosystem services are all the benefits that humanity receives from ecosystems. In other words, these are services for providing humanity with natural resources, a healthy habitat, and other ecologically and economically significant “products”. Among the numerous ecosystem services, those that provide resources (food, water, forest, raw materials), regulate processes in ecosystems (impact on the climate, control over floods, natural disasters, quality of water resources, etc.), provide cultural and social services (aesthetic and spiritual values of nature) and support the functioning of ecosystems (soil formation, photosynthesis, nitrogen cycle, etc.) can be selected. Unfortunately, the modern paradigm of environmental management does not take this assessment into account and, accordingly, the adoption of an ecologically important decision is evaluated unilaterally and does not take all aspects of the use of the estuary ecosystem into account. Today, there are various approaches to the assessment of ecosystem services. Thus, the Ramsar Committee, within the framework of wetland management, proposed a rapid assessment of ecosystem services (Resolution XIII.17). RAWES (Rapid Assessment of Wetland Ecosystem Services) practical approach was designed as a simple and rapid assessment system that draws on data from existing research but does not include detailed quantitative assessment. For a more efficient and quantitative assessment of ecosystem services, a cost evaluation should be used [17, 18].

The **second block** of the systemic decision-making scheme for estuary management is based on the implementation of the ***decision support system***. The essence of the management process is to make a decision – it is the choice of a course of action from a set of existing alternative options. In such conditions, the problem of choosing the most rational and effective solutions, that is, the best solutions, becomes one of the most important tasks of production management [16].

This system is designed to support various types of activities when making decisions on sustainable estuary use, restoration and management of the ecological state of the marine environment with achieving socio-ecological and economic profit. The application of the system ensures a thorough and objective analysis of the subject area when making decisions in difficult conditions. In modern conditions, this approach helps to make management decisions, taking more than one environmental factor into account and makes it possible to assess the short- and long-term effects of the implementation of management measures. The multi-vector and holistic approach of this information technology allows state management bodies, private investment institutions, and local communities to decide on the most appropriate scenario for managing local marine ecosystem in order to obtain the best socio-ecological and economic effect.

This system is based on 4 components:

Component 1. Database management system. Provides the ability to accumulate and process primary data. It includes the following databases: climatic, hydrometeorological, water quality, diversity of flora and fauna, natural resources and their use, recreational resources and their use.

Component 2. Geoinformational system. Allows to visualize the decision-making process and demonstrate the scale of changes or potential consequences from the implementation of management decisions.

Component 3. Mathematical and predictive models. This component is based on the broad involvement of mathematical modelling of all processes that are observed during the interaction of living beings with each other and the environment under the conditions of intense anthropogenic load.

Component 4. Informational and management system for choosing strategic and operational decisions. Provides an opportunity to predict possible changes in the ecosystems based on database analysis using hydrological and climate models. This, in turn, allows to form possible scenarios of ecosystem development. With the use of dynamic flow charts, it will be possible to choose a strategic and operational decision or a specific management measure, which will be aimed at overcoming environmental and socio-economic risks.

The **third block** of the systemic decision-making scheme for estuary management is dedicated to the implementation of the decisions made and includes 4 stages.

Stage 1. Environmental assessment of decisions and projects. This stage involves the completion of legally regulated evaluation processes of planned measures. Depending on the type of activity, Strategic Environmental Assessment and Environmental Impact Assessment are distinguished. Strategic Environmental Assessment (SEA) is a procedure that is necessary in order to determine, describe and evaluate the consequences affecting the environment and the health of the population through the implementation of state planning documents (urban planning documentation: a master plan, a detailed plan of the territory or a territory zoning plan, schemes of district planning, strategies, national programs, state target programs and other programs and program documents that are developed and/or subject to approval by the state authority, local self-government body), development of measures to prevent, reduce and mitigate possible negative consequences [19]. The Environmental Impact Assessment procedure (EIA) is designed to identify the nature, intensity and degree of danger of the impact of any type of planned economic activity on the state of the environment and the health of the population [20].

Stage 2. Implementation of environmental measures. As part of this stage, the planned activities for solving environmental problems of a specific body of water are being implemented. It should be noted that expert supervision of measure implementation and ecological and economic audits are integral tools within this stage. Quite often, non-compliance with technological processes or changes in design solutions occur during the implementation of measures.

Stage 3. Efficiency evaluation. The effectiveness measure implementation of measures is the final condition of ecological management. Thus, estuary management aims to solve not only environmental problems, but also take social and economic aspects into account. That is why efficiency evaluation should be based on the assessment of the state of indicator species and habitats, as well as on socio-economic indicators in the region of implementation of ecological management projects.

Stage 4. Search for new solutions and their improvement. The cyclic nature of ecological management is an important component of the continuous development and preservation of the natural resource potential of estuaries. Given that the estuaries of the region are complex natural multicomponent systems, changes in which can occur quite rapidly, it is necessary to include constant improvement of control elements. It is also important to note that our knowledge and management methods are constantly improving, and this, in turn, can contribute to the search for more effective measures to restore these hydroecosystems.

3. Conclusions

The Azov-Black Sea coast is represented by a significant number of estuaries and bays, which functioned for a long time thanks to an artificial connection with the sea. Molochny, Berezansky, Tyligulsky, Tuzlovsky estuaries, Eastern Sivash, and others are among them. They have important scientific, social and environmental significance. Most of them are included in the nature protection territories of Ukraine as national parks and have the status of wetlands of international importance. On the other hand, they are important from the socio-economic point of view, since reproduction and feeding of fish takes place in their water areas, and in the future, fishery.

The functioning of most estuaries in the region has always been related to the level of water exchange through artificial channels with Azov or Black Sea. For a long time, the management of these bodies of water took place spontaneously and was aimed at the formation of various ecological states. The lack of a systemic concept in the development of estuary management plans does not make it possible to make the necessary management decision. An important element in choosing the necessary solutions is the evaluation of ecosystemic services, as a tool for finding a balance between ecological, social and economic directions of estuary use. These assessments should determine the development vector of the estuary ecosystem, which will ensure the rational use of its natural resource potential.

Despite the obvious need to introduce a systemic approach to decision-making for estuary management, there are currently no methods of holistic assessment of their condition and decision-making strategies within the framework of ecological management. The proposed comprehensive approach is a practical tool for ensuring balanced nature management of the investigated hydroecosystems. Developed scheme of stages of systemic decision-making for estuary management is based on the implementation of successive stages, with a multi-component decision support system functioning in its centre. This scheme is cyclical and requires constant improvement of the decisions made and evaluations of the effectiveness of measures.

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References

[1] UN General Assembly (73rd sess : 2018-2019) 2019 United Nations Decade on Ecosystem Restoration (2021-2030) : resolution / adopted by the General Assembly URL https://digitallibrary.un.org/record/3794317

[2] Trueblood D, Almazán-Casali S, Arnott J, Brass M, Lemos M C, Matso K, Read J, Vaccaro L and Wondolleck J 2019 *Coastal Management* **47**(3) 337–346 URL https://doi.org/10.1080/08920753.2019.1598221

[3] Pendleton-Jullian A 2009 Design education and innovation ecotones URL https://fourplusone.files.wordpress.com/2010/03/apj_paper_14.pdf

[4] Carvalho T M and Fidélis T 2013 *Land Use Policy* **34** 134–145 ISSN 0264-8377 URL https://doi.org/10.1016/j.landusepol.2013.02.007

[5] Heap A D, Bryce S, Ryan D, Radke L, Smith C, Smith R, Harris P T and Heggie D 2001 Australian estuaries and coastal waterways: A geoscience perspective for improved and integrated resource management : A report to the national land & water resources audit theme 7: Ecosystem health Report National Land & Water Resources Audit Canberra, Australia URL https://ecat.ga.gov.au/geonetwork/srv/api/records/a05f7892-b599-7506-e044-00144fdd4fa6

[6] Fulford R S, Russell M, Hagy J D and Breitburg D 2020 *Global Ecology and Conservation* **21** e00892 ISSN 2351-9894 URL https://doi.org/10.1016/j.gecco.2019.e00892

[7] Romashchenko M I, Khvesyk M A and Mykhailov Y O (eds) 2015 *Vodna stratehiia Ukrainy na period do 2025 roku (naukovi osnovy)* (Kyiv: Komprint)

[8] Strokal V and Kovpak A 2020 *Scientific journal "Biological Systems: Theory and Innovation"* **11**(4) 35–56 URL https://doi.org/10.31548/biologiya2020.04.004

[9] Sazonets I and Pokul O 2015 *Socio-economic research bulletin* (3(58)) 198–205 URL http://vsed.oneu.edu.ua/collections/2015/58/pdf/198-205.pdf

[10] Loboda N S and Gopchenko E D 2016 *Water regime and hydroecological characteristics of the Kuyalnytsky estuary* (Odesa: TES)

[11] Minicheva G, Demchenko V and Sokolov Y 2021 *E3S Web of Conferences* **255** 01008 URL https://doi.org/10.1051/e3sconf/202125501008

[12] Demchenko V O, Vinokurova S V, Chernichko I I and Vorovka V P 2015 *Environmental Science & Policy* **46** 37–47 ISSN 1462-9011 enhancing environmental management and policy-making in the Black Sea catchment through improved data sharing URL https://doi.org/10.1016/j.envsci.2014.08.015

[13] Minicheva G G and Sokolov E V 2015 *Naukovi zapysky Ternopilskoho natsionalnoho pedahohichnoho universytetu imeni Volodymyra Hnatyuka. Seriia Biolohichna* (3-4(64)) 446–459 URL http://dspace.tnpu.edu.ua/bitstream/123456789/5865/1/Minicheva.pdf

[14] Kvyatkovska L A 2013 *Bulletin of social and economic research* (1(48)) 85–89 URL http://dspace.oneu.edu.ua/jspui/handle/123456789/3132

[15] Afanasyeva S O and Manturova O V 2019 *Management of the transboundary Dniester basin: establishment of reference indicators for assessing the ecological state of surface water bodies* (Kyiv: Department)

[16] Hrabovetskyy B Y 2010 *Methods of expert evaluations: theory, methodology, directions of use* (Vinnytsia: VNTU)
[17] Degtyar N V 2012 *Efficient economy* (2)
[18] Mishenin Y V and Degtyar N V 2015 *Marketing and innovation management* **6**(2) 243–257 URL https://armgpublishing.com/journals/mmi/volume-6-issue-2/article-21/
[19] Verkhovna Rada of Ukraine 2018 On Strategic Environmental Assessment URL https://zakon.rada.gov.ua/laws/show/2354-19?lang=en#Text
[20] Verkhovna Rada of Ukraine 2015 On Environmental Impact Assessment URL https://zakon.rada.gov.ua/laws/show/2059-19?lang=en

PAPER • OPEN ACCESS

Chromosomes of *Pelophylax ridibundus* Pallas, 1771 in different population systems of southern Ukraine

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Chromosomes of *Pelophylax ridibundus* Pallas, 1771 in different population systems of southern Ukraine

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Abstract. This paper provides the comparative morphological analysis of *P. ridibundus* chromosomes in different population systems of southern Ukraine. A certain variability and heteromorphism of individual homologs and of whole chromosome pairs was established. The chromosomes of *P. ridibundus* in populations consisting of a single species (Crimea, Zalisne, Arabat Spit) are relatively stable in quantitative and qualitative terms. Karyotypes are more variable in the lower reaches of the Dnipro River and Kharkiv Region, where the hybridogenic taxon *P. esculentus* lives together with *P. ridibundus*. It is assumed that such a relative constancy of chromosomes of southern Ukrainian *P. ridibundus* in pure RR-systems indicates both a high potential of their resistance to factors and an intraspecific genetic balance. This study is especially important in terms of conservation and enhancement of genetic and biological diversity, which mainly ensures the sustainability of ecosystems functioning.

1. Introduction

The South of Ukraine is characterized by a unique biological and genetic diversity of both typical widespread species and rare ones, which can preserve their unique relict nature with their own mechanisms of evolution and speciation [1]. What is interesting here is the hybridogenic speciation as a special source of increasing biological diversity, and this requires a new strategy for its assessment, protection and preservation. *Pelophylax ridibundus* (Pallas, 1771) is involved in all these processes. It is the most common typical species of amphibians of freshwater reservoirs of southern Ukraine and one of the parent species of the hybridogenic complex of green frogs of the genus Pelophylax. The vast majority of "pure" RR populations of *P. ridibundus* are distributed in the southern and southeastern parts of Ukraine. In other regions, it is often found in a complex with other species, namely P. lessonae and the hybrid taxon *P. esculentus*.

It is known that *P. ridibundus* is considered to be a complex of cryptic species. According to the analysis of mitochondrial and nuclear DNA, it was established that this species, in particular in the south of Ukraine and Crimea, is represented by two genetically differentiated forms – "western" (= Central European – *P. ridibundus*) and "eastern" (= Anatolian P. cf. bedriagae) [2, 3]. On the basis of our morphological studies and the latest literature data, it has been preliminarily proven that P. cf. bedriagae lives in Crimea, while *P. ridibundus* lives in the lower reaches of the Dnieper and further to the north and west. We also assume that P.

cf. bedriagae, might inhabit southeastern Ukraine, connected with the small rivers of the Azov region. Almost all known studies in this area are based on molecular and genetic data. It is quite important at this stage to establish more "visible" diagnostic traits, in particular at the level of ecology, morphology, and chromosomal indicators. The latter are important given the fact that amphibians are characterized by stable chromosomal conservatism, in which the same number of chromosomes is characteristic not only for species, but also for genera and families. Since it is the karyotype that ensures the stability of the existence of the species, therefore it is important to investigate how karyologically stable this species is, especially in the conditions of southern Ukraine. The importance of such features is essential from the point of view of protection, preservation, and increase of biological diversity, which is based on complex invisible genetic mechanisms, which can have great potential for understanding the role of hybridization as a source of speciation.

2. Research aim and objectives

The aim of the study was to identify specific characteristics at the level of karyotypes and to conduct a comparative morphological analysis of *P. ridibundus* chromosomes from different populations of southern Ukraine, including the Crimea.

3. Material and methods

The study was carried out in accordance with all modern requirements for the handling of experimental objects. Eight individuals of *P. ridibundus* were used in the study. For comparison of karyotypes, typical populations of *P. ridibundus* were selected (figure 1): Kherson Region, Henichesk District, Arabat Spit, recreation center "Valok" – 1 specimen (point 1); Kherson region, Hola Prystan District, near Stara Zburyivka village – 2 specimens (point 3); Crimea, Bakhchysarai District, village Zalisne (the material was collected before 2013) – 3 specimens (point 4) and a more distant point where the relevant population systems are widespread – Kharkiv Region, Izium District, near Snizhkivka village – 2 specimens (point 2).

A total of 49 metaphase plates were analyzed, 20 of which were selected for morphological

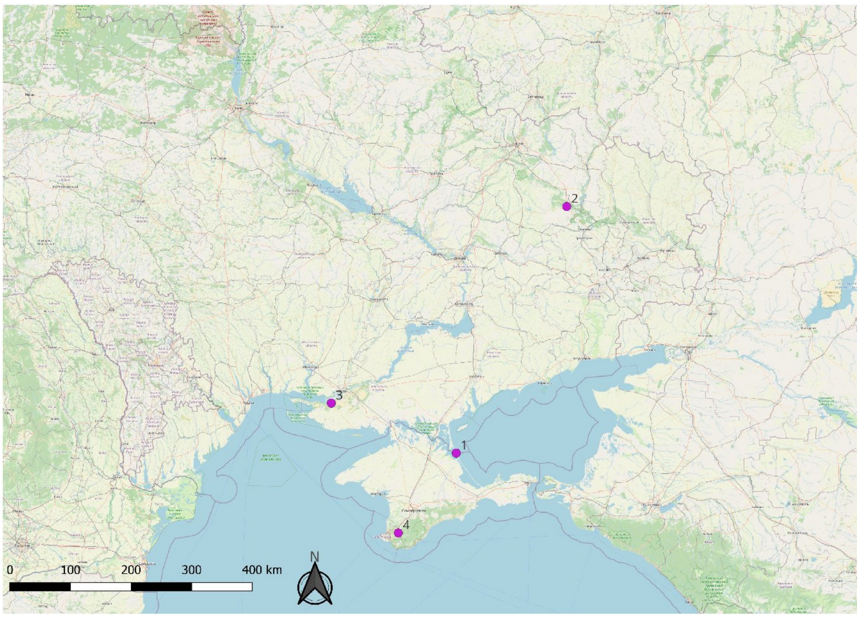

Figure 1. Populations of *P. ridibundus* used for analysis (the points are described in the text).

analysis. The preparation methods of karyological preparations, video recording, analysis and karyotyping of chromosomes, peculiarities of homologues selection and their typing are described in detail in our previous works.

4. Results

The standard karyotype of *P. ridibundus* is symmetrical and represented by two-armed chromosomes. It is characterized by the diploid number of 2n = 26, and the number of arms of N.F. = 52. The karyotype includes 5 pairs of large and 8 pairs of small chromosomes. The 1^{st} is a large metacentric, the 2^{nd}, 3^{rd} and 4^{th} pairs of chromosomes are submetacentric, the 5th pair is the smallest metacentric in the group of large chromosomes. The 6^{th} and 7^{th} pairs are also metacentrics among small chromosomes. The 8^{th} and 9^{th} pairs are represented by subtelocentric chromosomes (on some plates they can be submetacentric), especially the 9^{th} pair, which is characterized by a certain variability, since there is a secondary band on its long arm. The 10^{th}, 11^{th}, 12^{th}, and 13^{th} pairs are submetacentrics. The formula of the *P. ridibundus* karyotype is 4 meta-(m) + 7 submeta-(sm) + 2 subtelocentric-(st), 2n = 26, N.F. = 52.

First of all, it should be noted that all the analyzed metaphase plates and karyograms correspond to the standard karyotypes of *P. ridibundus*, but at the same time there is a certain variability and heteromorphism of individual homologs and of whole chromosome pairs. Particular attention should be paid to the study and clarification of the standard types of the last 4 pairs of chromosomes. Regarding the 10^{th} pair, it can be said that, in contrast to the indicated submetacentric type, in the vast majority it is represented by subtelocentric homologs. All analyzed plates show secondary bands on the long arm of the 9^{th} chromosome pair, which is not always characteristic of other closely related species, such as the hybridogenic *P. esculentus*. The chromosomes of *P. ridibundus* from Crimea and the Arabat Spit are relatively more stable in terms of quantity and quality (figure 2). Homologs are easily selected, even with total coloring.

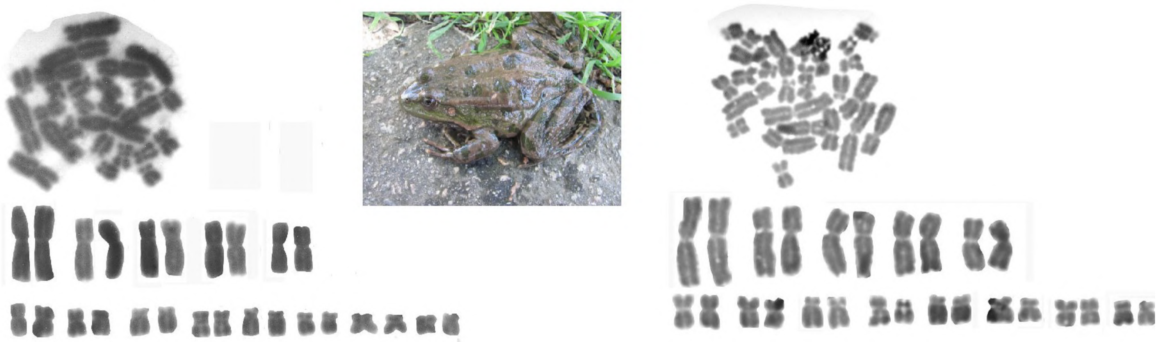

Figure 2. Metaphase plates and karyograms of *Pelophylax ridibundus* from southern Ukraine (Crimea, Bakhchysarai District, Zalisne village and Kherson Region, Arabat Spit).

The chromosomes are more variable in the karyotypes of *P. ridibundus* from the lower reaches of the Dnipro and Kharkiv Region (figure 3). Pairs often include chromosomes, which are different in size, but identical in morphology. This may be typical for the first pair of chromosomes, which was repeatedly emphasized in our previous studies. Heteromorphism of individual pairs and homologs is also found among the group of small chromosomes, especially the 6th, and the last three (11^{th}, 12^{th}, 13^{th}). Incomplete sets are often found, which is typical for all analyzed populations. More often homologs or even whole pairs are lost among the small chromosomes (figure 4). Among the large ones, homologs of the 5th pair can be lost occasionally (figure 5).

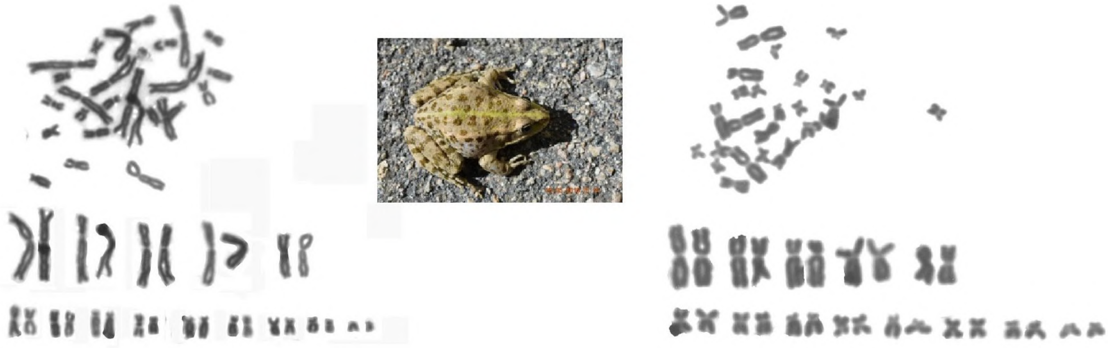

Figure 3. Metaphase plates and karyograms of *Pelophylax ridibundus* from Kherson region, Hola Prystan District, near Stara Zburyivka village, and Kharkiv Region, near Snizhkivka village.

Figure 4. Metaphase plates and karyograms of *Pelophylax ridibundus* with incomplete sets of chromosomes (Kherson Region, Hola Prystan District, near Stara Zburyivka village (1–2) and Kharkiv Region, near Snizhkivka village (3)).

Figure 5. Metaphase plates and karyograms of *Pelophylax ridibundus* with incomplete sets of chromosomes (Crimea, Bakhchysarai District, Zalisne village (1–3) and Kherson Region, Arabat Spit (4).

5. Discussion

First of all, the prevalence of population systems of green frogs in Ukraine should be mentioned. There are pure and mixed populations of parental species – RR, LL, RL, hemiclonal mixed – RE, LE, REL, and hybridogenic EE-type systems. In southern Ukraine, the most common are populations of *P. ridibundus* (RR) and mixed semi-clonal systems – RE and REL with different ploidy, abundance, and specific sexual structure. In different parts of their range, they have corresponding percentages, genetic structure, and other specific population characteristics [4].

The main result of the conducted comparative morphological analysis is the relative stability of *P. ridibundus* chromosomes in RR-populations (Crimea, Arabat Spit). Perhaps in such populations *P. ridibundus* has a more homogeneous genetic structure, which is manifested in the relative uniformity of chromosomal parameters, while incomplete sets are still present. Populations in which individuals with mosaic, i.e. with di-, tri-, and more, and aneuploid cell lines [5] are found mostly majority in *P. esculentus* and in all mixed population systems. One of the reasons for this may be a violation of the process of genome elimination or other mechanisms that arise during multidirectional hybridogenic speciation. According to our data, such karyotypes are also present in RR populations. As noted, *P. ridibundus* from southern Ukraine has an ambiguous systematic status, in particular in the Crimea there are two genetically differentiated forms [3,6] that can make their own adjustments of gamete production, introgression, genome composition, which can be manifested at the chromosomal level. It is interesting that alleles of the "western" form are less common than the "eastern" form in the south, moreover, it is believed that the territory of Crimea was inhabited by *P. ridibundus* of the Anatolian lineage, directly from the Caucasus. Probably, the extensive delta systems, which were formed in the regressive stages of the Black Sea basin during the Holocene, Pleistocene, to the southeast and west of the Crimea, contributed to this.

The karyotypes of *P. ridibundus* in the lower reaches of the Dnipro River and Kharkiv Region are much more variable. In this part of Ukraine *P. ridibundus* lives together with hybridogenic taxon *P. esculentus*. The RE-type population system has a very diverse genetic structure, with the presence of polyploids, a large diversity of parental genomes that are produced, transmitted, and inherited through complex genetic mechanisms [7–10]. Therefore, all these factors can be manifested in the variability of homologs, the qualitative and quantitative characteristics of chromosomes. Of course, we allow for the possibility that our results are related to geographical variability, different nature spiralization and condensation of the chromosomes and their individual parts, which can lead to heteromorphism of homologs.

6. Conclusion

The results of the study suggest that such a relative constancy of chromosomes of the southern Ukrainian *P. ridibundus* in pure RR-systems indicates a high potential of their resistance to factors and their intraspecific genetic balance. At the same time, we allow for the possibility of introgression between the "eastern" and "western" forms. *P. ridibundus* in mixed RE-systems has a certain genetic and ecological interaction in the process of hybridogenic reproduction that directly affects the morphology of the karyotype, which is manifested in the variability of homologs, their qualitative and quantitative characteristics. The presented materials are only preliminary and require confirmation with the use of comparative statistical methods of the relevant chromosomal indicators. It is also necessary to investigate the composition of the genome, the genetic structure, to what extent molecular variability is comparable with chromosomal variability, and how it is reflected in different populations of green frogs. This is especially important from the point of view of preserving and increasing the genetic and biological diversity, which mainly ensures the sustainability of ecosystems functioning.

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References

[1] Dufresnes C, Strachinis I, Suriadna N, Mykytynets G, Cogălniceanu D, Székely P, Vukov T, Arntzen J W, Wielstra B, Lymberakis P, Geffen E, Gafny S, Kumlutaş Y, Ilgaz Ç, Candan K, Mizsei E, Szabolcs M, Kolenda K, Smirnov N, Géniez P, Lukanov S, Crochet P A, Dubey S, Perrin N, Litvinchuk S N and Denoël M 2019 *Molecular Ecology* **28**(13) 3257–3270 URL `https://doi.org/10.1111/mec.15133`

[2] Dufresnes C and Mazepa G 2020 Hybridogenesis in water frogs *eLS* (Wiley) p 718–726 URL `https://doi.org/10.1002/9780470015902.a0029090`

[3] Plötner J, Uzzell T, Beerli P, Akın Ç, Bilgin C C, Haefeli C, Ohst T, Köhler F, Schreiber R, Guex G D, Litvinchuk S N, Westaway R, Reyer H U, Pruvost N and Hotz H 2010 Genetic divergence and evolution of reproductive isolation in eastern mediterranean water frogs *Evolution in Action* ed Glaubrecht M (Berlin, Heidelberg: Springer Berlin Heidelberg) p 373–403 URL https://doi.org/10.1007/978-3-642-12425-9_18

[4] Dubey S, Maddalena T, Bonny L, Jeffries D L and Dufresnes C 2019 *BMC Evolutionary Biology* **19**(1) 164 URL https://doi.org/10.1186/s12862-019-1482-4

[5] Ogielska M, Kazana K and Kierzkowski P 2008 *Zoosystematics and Evolution* **77**(1) 65–70 URL https://doi.org/10.1002/mmnz.20010770111

[6] Akın Ç, Can Bilgin C, Beerli P, Westaway R, Ohst T, Litvinchuk S N, Uzzell T, Bilgin M, Hotz H, Guex G D and Plötner J 2010 *Journal of Biogeography* **37**(11) 2111–2124 URL https://doi.org/10.1111/j.1365-2699.2010.02368.x

[7] Biriuk O V, Shabanov D A, Korshunov A V, Borkin L J, Lada G A, Pasynkova R A, Rosanov J M and Litvinchuk S N 2016 *Journal of Zoological Systematics and Evolutionary Research* **54**(3) 215–225 URL https://doi.org/10.1111/jzs.12132

[8] Dedukh D, Litvinchuk S, Rosanov J, Shabanov D and Krasikova A 2017 *BMC Evolutionary Biology* **17**(1) 220 URL https://doi.org/10.1186/s12862-017-1063-3

[9] Dufresnes C, Mazepa G, Jablonski D, Oliveira R C, Wenseleers T, Shabanov D A, Auer M, Ernst R, Koch C, Ramírez-Chaves H E, Mulder K P, Simonov E, Tiutenko A, Kryvokhyzha D, Wennekes P L, Zinenko O I, Korshunov O V, Al-Johany A M, Peregontsev E A, Masroor R, Betto-Colliard C, Denoël M, Borkin L J, Skorinov D V, Pasynkova R A, Mazanaeva L F, Rosanov J M, Dubey S and Litvinchuk S 2019 *Molecular Phylogenetics and Evolution* **141** 106615 URL https://doi.org/10.1016/j.ympev.2019.106615

[10] Shabanov D, Vladymyrova M, Leonov A, Biriuk O, Kravchenko M, Mair Q, Meleshko O, Newman J, Usova O and Zholtkevych G 2020 Simulation as a method for asymptotic system behavior identification (e.g. water frog hemiclonal population systems) p 392–414 URL https://doi.org/10.1007/978-3-030-39459-2_18

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Impact of mini-hydropower on the chemical composition of water and phytoplankton of the reservoirs of the Forest-Steppe of Ukraine

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Impact of mini-hydropower on the chemical composition of water and phytoplankton of the reservoirs of the Forest-Steppe of Ukraine

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Abstract. The peculiarities of the transformation of river ecosystems in the reservoir at the construction of mini-hydropower plants have been found out. It was also found that the large-scale hydraulic engineering in the second half of the XX century caused significant changes in environmental conditions in the waterbodies, which has led to negative dynamics of species richness of aquatic organisms in general and phytoplankton in particular. Reservoir building has a significant negative impact on river ecosystems: currents slow down and disappear, canals become silted up, harmful substances of household and industrial waste gradually accumulate. The transformation of rivers into lake-type reservoirs is also accompanied by changes in the species composition and structure of phytoplankton. Eutrophication of reservoirs becomes typical. All this leads to significant degradation in aquatic ecosystems.

1. Introduction

At the beginning and in the middle of the XX century, small hydropower plants (MHPPs) were built on a large number of small and medium-sized rivers in Ukraine. In the 1930-1980-s, there were estimated more than 1,500 of them, now there are only 98 ones [1]. The building of reservoirs has caused radical changes in the ecological condition of rivers. Currents slowed down or disappeared completely on large sections of riverbeds, water exchange began to be determined by the mode of operation of hydroelectric power plants. This dramatically changed, first of all, the hydrological and hydrochemical regimes of rivers [2]. Another consequence was siltation and accumulation of harmful substances from industrial, agricultural and domestic effluents, which also leads to changes in the hydrochemical regime, mainly due to increased concentrations of biogenic substances [3, 4].

At the beginning of the 21st century, scientists around the world came to the conclusion that rivers need to be revitalized. In practice, it is necessary to study each individual case in detail, and only after that a conclusion can be made about the feasibility of existing hydraulic structures. In the United States, about 900 dams were dismantled between 1990 and 2015. France and

Canada have also completed important dam removal projects. In Japan, the dismantling of dams began in 2012 [5–7].

Due to the plans for significant expansion of hydraulic engineering on small rivers of the Forest-Steppe of Ukraine, it is extremely important to find out the nature of the impact of MHPP on hydrochemical and hydrobiological regimes. An important aspect of the study is to identify patterns of composition, structure and functioning of hydrobionts under the conditions of transformation of river ecosystems into ponds and lakes. It appears extremely necessary to develop measures to minimize the harmful effects of HPPs for optimizing the state of reservoir ecosystems. This study is relevant in the framework of the European Framework Directive (WFD), adopted in 1992 in order to intercalibrate rivers and ensure the synchronization of research and the possibility of comparison and generalization of information [8, 9].

2. Material and methods

The study was conducted at 7 MHPP reservoirs located on Koropets River (Koropetske reservoir), Hnily Tikich River (Zvenygorodke and Lotashivske reservoirs), Hirsky Tikich River (Yurpilske and Hordashivske reservoirs) and Ros River (Steblivske and Korsun-Shevchenkivske reservoir). In accordance with the existing classification, small hydropower plants (SHPPs) include hydroelectric power plants with a capacity of 1 to 10 MW, mini-HPPs – from 200 to 1000 kW, micro HPPs – no more than 200 kW. So, the reservoirs of mini-hydroelectric power stations described in the article are: Koropetskaya HPP (250 kW), Zvenigorodskaya HPP (400 kW), Lotashiv HPP (420 kW). Yurpolska (not functioning), Gordashivska HPP (400 kW). Steblivska HPP (3.0 MW) and Korsun-Shevchenkivska HPP (1.2 MW) are already small HPPs.

The selection of material was carried out during expeditions in 2013-2020 in the warm period (from April to September). Data from hydrological yearbooks, kindly provided by the Geophysical Observatory of the Hydrometeorological Service of Ukraine in Kyiv, were used to study the dynamics of hydrological conditions of reservoirs in the region. Processing of hydrochemical water samples (64 samples) was carried out in a specialized chemical laboratory of the Ukrainian Hydrometeorological Institute UkrGMI. Temperature, hydrogen index (pH), and the amount of dissolved oxygen in water were determined directly on the reservoirs using the certified electronic device Ecotest-2000 (№ 19027-99 in the State Register). To examine phytoplankton, a Rutner bathometer was used (water samples were taken from a surface layer and a 1.5 m layer). Water was fixed with a 2% formalin solution. After settling, the sample volume was increased to 30-100 cubic using a siphon. Determination of the species and quantitative composition of algae was carried out jointly with the staff of the Institute of Hydrobiology of the National Academy of Sciences of Ukraine according to standard methods [10–12]. Assessment of water quality of fishery reservoirs and reservoirs of complex purpose was carried out according to SOU 05.01-37-385: 2006 [13]. Hygienic classification of bodies of water was carried out according to State Sanitary Rules and Regulations 2.2.4-171-10 2010 [14]. Ecological assessment of surface water quality was carried out using generally accepted methods [10, 15].

3. Results and discussion

Hydrochemical characteristics are important markers of the ecological status of waterbodies. In terms of the content of basic chemicals, the water of the reservoirs of the Forest-Steppe MHPP meets the state fishery standards (MPC) in most indices. A slight excess of the MPC for magnesium (in 1.09–1.15 times) was observed in the Yurpil and Korsun-Shevchenkivsky reservoirs. Exceeding the MPC for this element together with calcium leads to increased water hardness. However, the increasing change of water hardness has a positive effect on the state of aquatic organisms, and the decrease – on the contrary. In terms of salt composition, the water

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Table 1. Main hydrochemical characteristics of the MHPP reservoirs in the Forest-Steppe zone of Ukraine.

	Reservoirs*			
Index**	1	2	3	4
pH	7.63 ± 0.1	7.83 ± 0.1	7.80 ± 0.1	8.0 ± 0.1
Mineralization, mg/dm^3	463 ± 23.1	639.7 ± 22.4	661.5 ± 22.1	624.4 ± 20.3
Bicarbonates, mg/dm^3	301 ± 13.1	419.4 ± 13.3	411.7 ± 12.8	411.0 ± 12.9
Sulfates, mg/dm^3	28.0 ± 2.3	46.5 ± 4.9	53.3 ± 5.4	33.0 ± 3.9
Chlorides, mg/dm^3	24.9 ± 2.2	38.3 ± 3.7	44.6 ± 4.6	44.6 ± 3.8
Magnesium, mg/dm^3	27.2 ± 2.4	48.3 ± 3.1	44.2 ± 3.2	48.5 ± 5.3
Calcium, mg/dm^3	52.7 ± 4.6	48.5 ± 4.9	61.3 ± 6.7	44.0 ± 4.1
Hardness of water	4.9 ± 0.2	7.2 ± 0.2	7.2 ± 0.2	7.0 ± 0.2
Potassium, mg/dm^3	52.7 ± 4.4	11.9 ± 0.9	14.9 ± 1.3	13.3 ± 1.6
Sodium, mg/dm^3	18.4 ± 1.4	23.7 ± 2.3	30.0 ± 3.0	26.6 ± 2.9
Iron, mg/dm^3	0.04	0.05	0.03	0.03
Index**	5	6	7	MPC*
pH	8.0 ± 0.2	7.9 ± 0.2	7.7 ± 0.2	6.5–8.5
Mineralization, mg/dm^3	624.4 ± 25.2	536.9 ± 26.3	532.4 ± 23.3	1000
Bicarbonates.mg/dm^3	411.0 ± 14.1	341.6 ± 13.9	330.4 ± 12.8	
Sulfates, mg/dm^3	33.0 ± 3.2	35.75 ± 3.9	34.8 ± 3.3	100
Chlorides, mg/dm^3	44.6 ± 4.6	41.39 ± 3.7	39.7 ± 3.9	
Magnesium, mg/dm^3	48.4 ± 4.4	35.09 ± 3.7	35.7 ± 5.1	40
Calcium, mg/dm^3	55.8 ± 6.9	56.6 ± 3.8	55.5 ± 6.9	180
Hardness of water	7.1 ± 0.2	5.8 ± 0.2	5.6 ± 0.2	6.5–8.5
Potassium, mg/dm^3	13.3 ± 1.1	12.1 ± 1.1	12.5 ± 1.4	50
Sodium, mg/dm^3	26.6 ± 2.3	24.4 ± 2.2	24.4 ± 2.6	120
Iron, mg/dm^3	0.03 ± 0.001	0	0	0.1

Note: * Reservoirs: 1 – Koropetske, 2 – Zvenygorodske, 3 – Lotashivske, 4 – Yurpilske, 5 – Hordashivske, 6 – Steblivske, 7 – Korsun-Shevchenkivske;
** according to SOU 05.01-37-385:2006: pH 6,5–8,5; mineralization – 1000; sulfates – 100; magnesium – 40; calcium – 180; potassium – 50; sodium – 120; iron – 0.1.

of the studied reservoirs belongs to the bicarbonate-calcium type. Bicarbonates predominate in all investigated reservoirs (table 1).

According to the criteria of pollution by components of a salt composition, water in reservoirs, on average, was determined as having an index – 2.0, which applies to class II of category 2 (good, clean). According to ecological and sanitary indices (State Sanitary Rules and Regulations 2.2.4-171-10), the average value of the water quality category of reservoirs was determined as 3.66 (4.0), which applies to class IV of category 4 (satisfactory, slightly polluted).

Considering the biogenic substances, there was detected a significant excess of concentrations of nitrites and phosphates. Exceeding the MPC was observed for the following indices: in the reservoirs Koropetske (nitrite by 3.5 times), Steblivske (nitrite by 5.0 times) and Korsun-Shevchenkivske (nitrite by 20.0 times and ammonium nitrogen by 1.4 times). All this indicates significant decay processes or significant industrial and domestic effluents. Excess MPCs for phosphates are also related to this. The worst situation is observed in Steblivske (phosphates by 10.6 times) and Korsun-Shevchenkivske (phosphates by 10.2 times) reservoirs. The high levels

Table 2. Biogenic substances in the MHPP reservoirs in the Forest-Steppe zone of Ukraine.

	Reservoirs*			
Index**	1	2	3	4
Ammonium nitrogen, mgN/dm^3	0.03 ± 0.001	0.38 ± 0.001	0.08 ± 0.001	0.1 ± 0.001
Nitrogen nitride, mgN/dm^3	0.24 ± 0.02	0.04 ± 0.001	0.01 ± 0.0001	0.03 ± 0.001
Nitrogen nitrate, mgN/dm^3	1.01 ± 0.3	0.2 ± 0.002	0.06 ± 0.002	0.1 ± 0.001
Mineral nitrogen, mgN/dm^3	1.15 ± 0.4	1.5 ± 0.001	0.14 ± 0.01	0.24 ± 0.002
Phosphates, mgP/dm^3	0.09 ± 0.005	0.39 ± 0.003	0.39 ± 0.02	0.2 ± 0.002
Index**	5	6	7	MPC**
Ammonium nitrogen, mgN/dm^3	0.08 ± 0.001	0.161 ± 0.001	0.53 ± 0.01	0.39
Nitrogen nitride, mgN/dm^3	0.01 ± 0.002	0.36 ± 0.001	0.4 ± 0.01	0.02
Nitrogen nitrate, mgN/dm^3	0.06 ± 0.01	0.77 ± 0.006	0.82 ± 0.02	
Mineral nitrogen, mgN/dm^3	0.144 ± 0.06	0.93 ± 0.008	1.38 ± 0.04	-
Phosphates, mgP/dm^3	0.4 ± 0.002	0.51 ± 0.005	0.51 ± 0.03	0.05

Note: * names of reservoirs, as in table 1; ** according to SOU 05.01-37-385:2006 ammonium nitrogen – 0.39; nitrite nitrogen – 0.02; phosphates – 0.05.

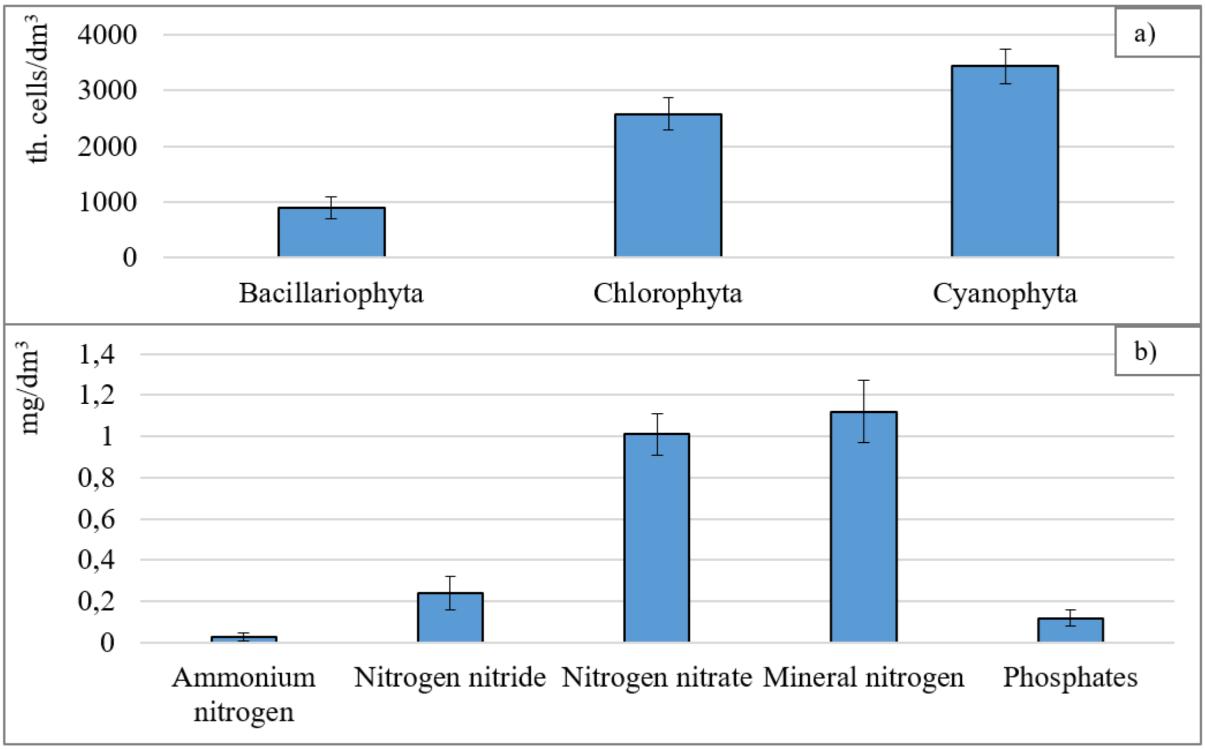

Figure 1. The ratio of the main groups of phytoplankton (a) and the amount of biogenic substances (b) in the Koropets reservoir.

(by 3.4–8.6 times) of phosphates were also detected in the rest of the reservoirs (table 2).

Phosphates are known to be primarily associated with detergents, so they are most abundant in reservoirs located in densely populated areas. The situation with biogenic substances is complicated by the regulation of river runoff arising as a result of reservoirs creation. Slowing down and disappearing of currents leads to the accumulation of harmful substances from runoffs. The lower parts of reservoirs and the reservoirs in the lower part of rivers are the most polluted.

The upper reaches of reservoirs are characterized by minimal indices of biogenic substances (nitrites – 0.054 ± 0.001; phosphates – 0.233 ± 0.02), middle parts (0.129 ± 0.01; 0.366 ± 0.03), lower parts (0.157 ± 0.015; 0.417 ± 0.04). These data clearly reveal the consequences of river regulation by the dams. The current is maintained in the upper reaches, and the nearest territory has a minimum amount of settlements. The middle and lower parts contain a predominant number of settlements, which are related to industrial, agricultural and domestic effluents. The decomposition of organic matter during eutrophication, which is the source of biogenic substance accumulation, is also the most significant there.

The above-mentioned hydrochemical parameters play an important role in the formation of groups of aquatic organisms, primarily phytoplankton. The phytoplankton excessive development (eutrophication) correlating with a significant excess of the MPC for biogenic substances, especially phosphates, was observed. A rectilinear dependence of the number of cyanophytes from the number of biogenic substances has been proved. On the other hand, an exaggeration of the amount of phosphates leads to inhibition of the activity of algae, especially diatoms. As shown above, the amount of phosphates depends on a number of reasons, among

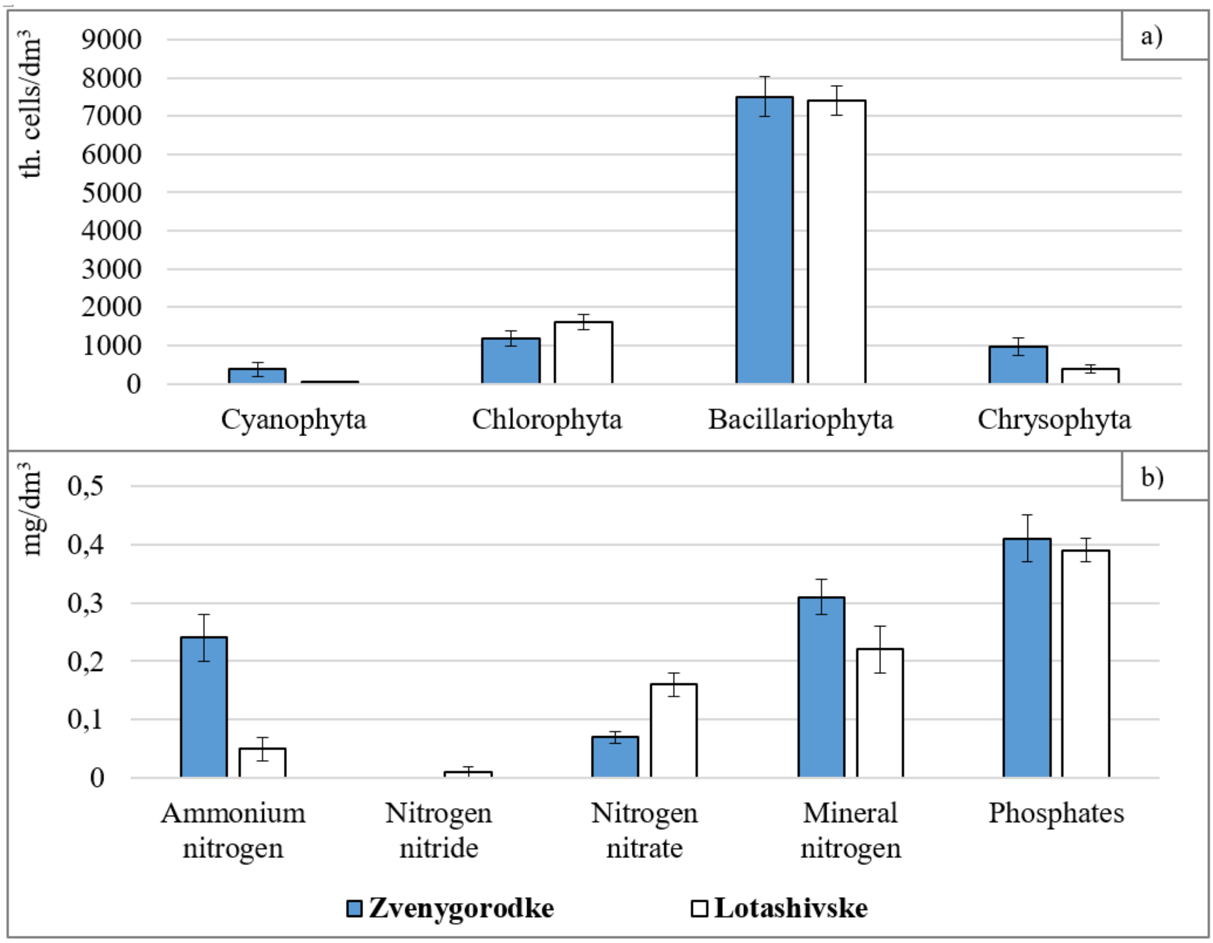

Figure 2. The ratio of the main groups of phytoplankton (a) and the amount of biogenic substances (b) in the reservoirs of Hnily Tikich River.

the most important are the size of the reservoir, the density of settlements on the banks and the area of reservoirs along with the flow. The same factors are observed highly influencing the phytoplankton abundance.

The amount of phosphates is not significant in the small Koropetske reservoir, but cyanophytes predominate there (figure 1).

The quantitative ratio of different taxonomic groups of algae in general and cyanophytes in particular differs in the reservoirs of the Gnily Tikich River. There is observed an another pattern. Thus, one of the two studied reservoirs on the Gnily Tikich River – Zvenigorodske one is located within the settlements and Lotashivske reservoir is located in sparsely populated areas. In addition, the Lotashivsky reservoir is upstream, and Zvenigorodske one is in the middle part. Having almost equal amounts of phosphates in these reservoirs, Zvenigorodske reservoir has 372 ± 23 thousand cells/dm^3 of cyanophytes while Lotashivske reservoir shows the minimum number of cyanophytes ($56 \geq \pm 11$ thousand cells/dm^3) and up to their total absence in the upper and middle parts (figure 2). There are much more diatoms in the studied reservoirs: 5960 ± 35 thousand cells/dm^3 in Lotashivsky reservoir and 7400 ± 43 thousand cells/dm^3 in Zvenigorodske reservoir (figure 2).

Similar results were obtained on the Hirsky Tikich River. Yurpilske reservoir is located in the upper reaches in sparsely populated areas. There is a minimal amount of biogenic substances and no cyanophytes. The number of diatoms is 4586 ± 41 thousand cells/dm^3. The Gordashivske reservoir is surrounded on two sides by settlements. Exceeding the MPC of phosphates was

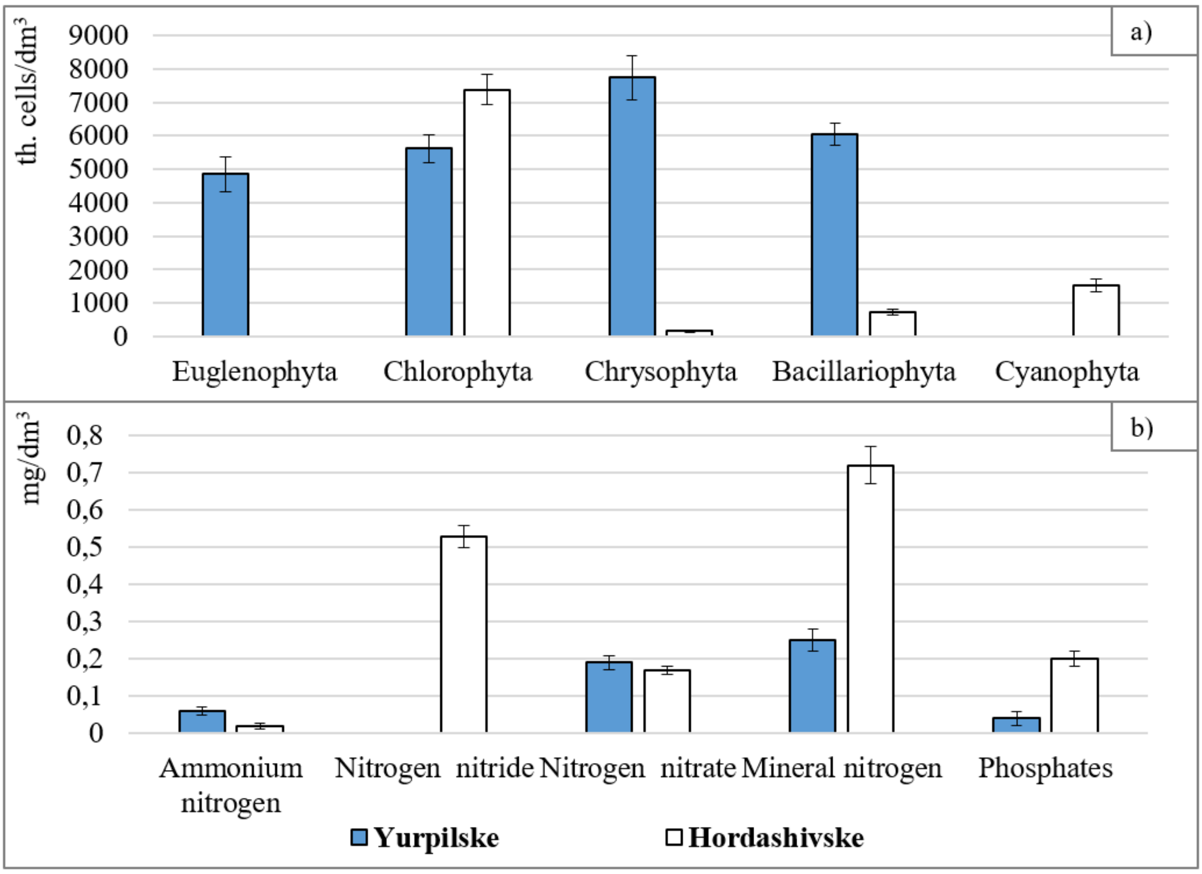

Figure 3. The ratio of the main groups of phytoplankton (a) and the amount of biogenic substances (b) in the reservoirs of Hirsky Tikich River.

observed there by 4 times. The cyanophytes (1529 ± 16 thousand cells/dm^3) were observed throughout the reservoir. The number of diatoms was observed by 6-9 times lower (730 ± 23 thousand cells/dm^3) comparing the previous reservoirs (figure 3).

The Steblivske and Korsun-Shevchenkivske reservoirs are located in the densely populated lower part of the Ros River. As shown above, there was observed a significant exceedances of the MPC for biogenic substances in these reservoirs. This significantly affected the species composition and abundance of phytoplankton: the number of cyanophytes is 3272 ± 45 thousand cells/dm^3 (Steblivske reservoir) and 5173 ± 52 thousand cells/dm^3 (Korsun-Shevchenkivske reservoir). The number of diatoms is much smaller: 1232 ± 21 thousand cells/dm^3 (Steblivsky reservoir) and 1366 ± 27 thousand cells/dm^3 (Korsun-Shevchenkivske reservoir) (figure 4).

The relation between the concentration of nitrites and phosphates and the amount of cyanophytes according to the results of correlation analysis is characterized as close ($R = 0.861$) (figure 5). The observed reservoirs were classified as β-mesosaprobic and β'-mesosaprobic in terms of saprobity and as mesotrophic (predominant type) in terms of trophicity.

4. Conclusions

In terms of the content of basic chemicals, the water of the reservoirs of the Forest-Steppe MHPP meets the state fishery standards (MPC) in most indices. A slight excess of the MPC for magnesium (by 1.09–1.15 times) was observed in the Yurpilske and Korsun-Shevchenkivske reservoirs. According to the criteria of pollution by components of a salt composition, water in reservoirs, on average, was determined as having an index – 2.0, which applies to class II of

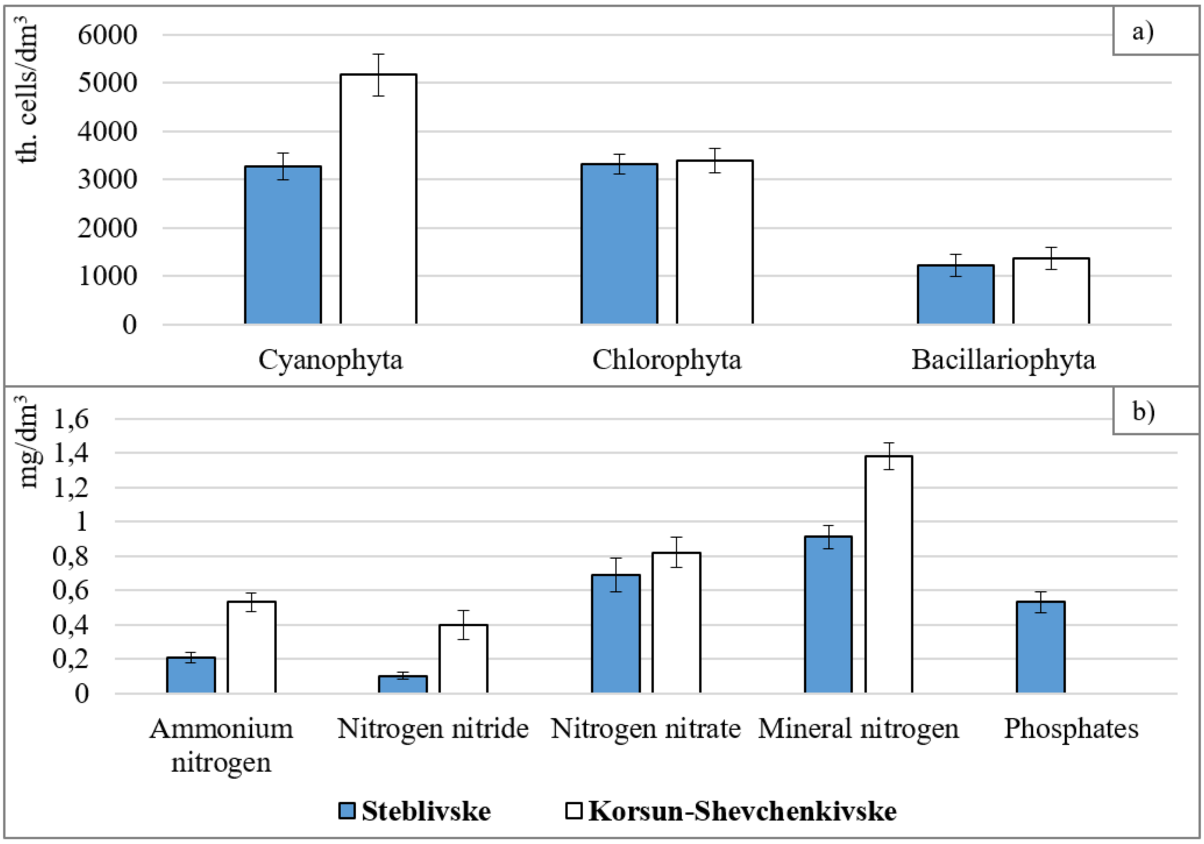

Figure 4. The ratio of the main groups of phytoplankton (a) and the amount of biogenic substances (b) in the reservoirs of Ros River.

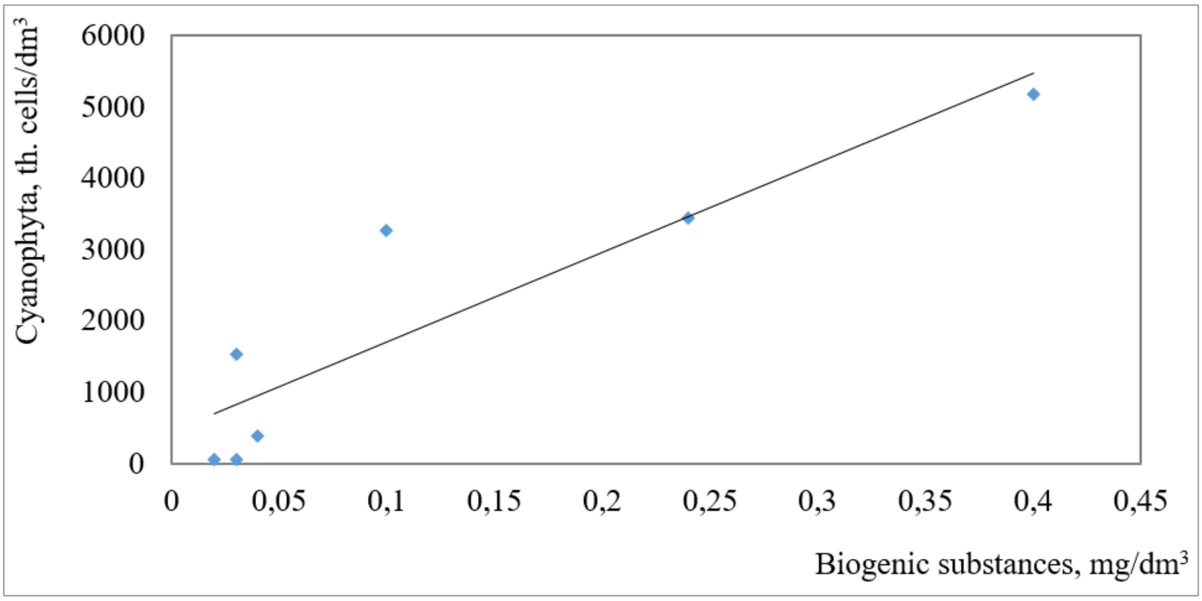

Figure 5. Correlation between the density of cyanophyte groups and the amount of biogenic substances in the studied reservoirs.

category 2 (good, clean). According to ecological and sanitary indices (State Sanitary Rules and Regulations 2.2.4-171-10), the average value of the water quality category of reservoirs was determined as 3.66 (4.0), which applies to class IV of category 4 (satisfactory, slightly polluted).

Hydrochemical indices of some basic chemical parameters and most biogenic substances exceeded or reached the MPC.

Thus, in the Koropetske reservoir the excess of biogenic substances is by 1.5–2.2 times; in the reservoirs of the Gnily Tikich River – by 1.2–12.0 times; in the reservoirs of the Gorsky Tikich River – by 1.4–3.3 times; in the reservoirs of the Ros River – by 1.4–40 times. This in turn causes excessive development of phytoplankton, leading to "blooming" of water with excessive development of cyanobacteria.

A close relation has been figured out between the concentration of cyanobacteria and the amount of biogenic substances in the water, which depends on the territorial location of the reservoir. The effect of cyanobacteria on certain groups of algae and other aquatic organisms has been elucidated. Four groups of algae (Euglenophyta, Chrysophyta, Chlorophyta, Bacillariophyta), the overall density of which reaches 7000 thousand cells/dm^3, are found in case of absence or minimum number of cyanobacteria (up to 3000 thousand cells/dm^3) in the reservoirs. This was observed in the Yurpilske, Lotashivske and Zvenyhorodske reservoirs. On the contrary, if the density of Cyanophyta increases over 5000 thousand cells/dm^3, it remains only two groups of algae (Chlorophyta and Bacillariophyta) with an overall density of 1000–3000 thousand cells/dm^3. This was observed in the reservoirs Steblivske and Korsun-Shevchenkivske. During the intensive "blooming" of water in the studied reservoirs, the suffocations periodically occurred, leading to the death of fish, crustaceans and other aquatic organisms.

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References

[1] Misiuk M, Podorozhna T, Balynska O, Kucher O and Burlakov O 2020 *E3S Web of Conferences* **154** 06003 URL https://doi.org/10.1051/e3sconf/202015406003
[2] Khilchevskyi V K, Kurylo S M, Dubnyak S S, Savitskii V N and Zabokrytska M R 2009 *Hydroecological state of the basin of the river Ros* (Kyiv: Nika-Tsentr)
[3] Afanasyev S O 2019 *Hydrobiological Journal* **55**(2) 3–17 ISSN 0018-8166 URL https://doi.org/10.1615/HydrobJ.v55.i2.10
[4] Bănăduc D, Simić V, Cianfaglione K, Barinova S, Afanasyev S, Öktener A, McCall G, Simić S and Curtean-Bănăduc A 2022 *International Journal of Environmental Research and Public Health* **19**(24) 16570 ISSN 1660-4601 URL https://doi.org/10.3390/ijerph192416570
[5] Hart D D, Johnson T E, Bushaw-Newton K L, Horwitz R J, Bednarek A T, Charles D F, Kreeger D A and Velinsky D J 2002 *BioScience* **52**(8) 669–682 ISSN 0006-3568 URL https://doi.org/10.1641/0006-3568(2002)052[0669:DRCAOF]2.0.CO;2
[6] Lyche Solheim A, Globevnik L, Austnes K, Kristensen P, Moe S J, Persson J, Phillips G, Poikane S, van de Bund W and Birk S 2019 *Science of The Total Environment* **697** 134043 ISSN 0048-9697 URL 10.1016/j.scitotenv.2019.134043
[7] Maavara T, Chen Q, Van Meter K, Brown L E, Zhang J, Ni J and Zarfl C 2020 *Nature Reviews Earth & Environment* **1**(2) 103–116 ISSN 2662-138X URL https://doi.org/10.1038/s43017-019-0019-0
[8] Council of the European Union 1992 *Official Journal* **L 206** 0007 – 0050
[9] Bennett C, Owen R, Birk S, Buffagni A, Erba S, Mengin N, Murray-Bligh J, Ofenböck G, Pardo I, van de Bund W, Wagner F and Wasson J G 2011 *Hydrobiologia* **667**(1) 31–48 ISSN 1573-5117 URL https://doi.org/10.1007/s10750-011-0635-2
[10] Arsan O M, Davydov O A, Diachenko T M, Yevtushenko M Y, Zhukynskyi V M, Kyrpenko N I, Kipnis L S, Klenus V H, Konovets I M, Lynnyk P M, Liashenko A V, Oliinyk H M, Pashkova O V, Protasov O O, Sylaieva A A, Sytnyk Y M, Stoika Y O, Timchenko V M, Shapoval T M, Shevchenko P H, Shcherbak V I, Yuryshynets V I and Yakushyn V M 2006 *Methods surveying of surface water studies* (Kyiv: Logos)
[11] Sukhodol'skaya I L, Manturova O V and Griuk I B 2015 *Hydrobiological Journal* **51**(5) 50–61 ISSN 0018-8166 URL https://doi.org/10.1615/HydrobJ.v51.i5.50
[12] Prokopchuk Y I and Manturova O V 2017 *Hydrobiological Journal* **53**(5) 38–45 ISSN 0018-8166 URL https://doi.org/10.1615/HydrobJ.v53.i5.40
[13] 2006 SOU 05.01-37-385:2006 Voda rybohospodarskykh pidpryiemstv. Zahalni vymohy ta normy [SOU 05.01-37-385:2006 Water of fishery enterprises. General requirements and norms] URL https://www.twirpx.com/file/3178429/
[14] Ministry of Health of Ukraine 2010 State sanitary rules and rules "Hygienic requirements for drinking water intended for human consumption" (DSanPin 2.2.4.-171-10) URL https://zakon.rada.gov.ua/laws/show/z0452-10
[15] Tsos O A 2017 *Man and Environment. Issues of Neoecology* **27**(1-2) 71–76 URL https://periodicals.karazin.ua/humanenviron/article/view/9172

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Factor analysis of the Wind Farm LLC wind park (Donetsk region, Ukraine) impact on bats based on the index of their activity and dynamics of species diversity

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Factor analysis of the Wind Farm LLC wind park (Donetsk region, Ukraine) impact on bats based on the index of their activity and dynamics of species diversity

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Abstract. In 2019-2020, research on the vocal activity of bats was carried out on the territory of the Wind Farm LLC wind park (800 MW), which is planned to be built near Mariupol (Donetsk region, Ukraine). There were used three methods of material collection: research on the vantage points, on transects and at a stationary point throughout the night. The total number of registered voices is 1554 signals, 695 of which are recorded in 2019 and 859 in 2020. The article shows the dynamics of voice activity by seasons and phases of the life cycle. Based on the activity index of mice, the dynamics of this indicator by months is shown. Forage and migratory behaviour of bats, calculated by determining the index of their activity, shows the average values. An analysis of the territorial distribution shows that bats confined to settlements and open water bodies. The species composition of bats, identified for 1235 signals registered in the territory of the projected wind farm, is stable and represented by widespread at least 10 species belonging to 6 taxonomic ranks. There were revealed some wind turbine generators near which the implementation of minimization measures is required. In total, according to forecasts, there are 10-16 such wind turbine generators within the Wind Farm LLC wind park. Monitoring the state of bats in the project area both during the construction of the wind farm and its operation is mandatory for the development and implementation of measures to minimize the possible negative impact on bats.

1. Introduction

The main purpose of the methodological approaches is to summarize the basic requirements for studying the activity of bats for the needs of the Project, which relates to the construction of a wind farm together with ancillary infrastructure including a power transmission line.

2. Material and methods

Methods for collecting and analyzing information on the behavior of bats are based on national and international practices [1–3].

2.1. Research area

The research area is located 17 km west of Mariupol (Donetsk region, Ukraine), where the construction of the wind farm is planned (figure 1). The research area covers the entire territory of the Wind Farm LLC wind park together with the 330 kV power transmission line (PTL-330).

The current location of the planned project with the proposed location of vantage points is presented in figure 1 and their characteristics is in table 1.

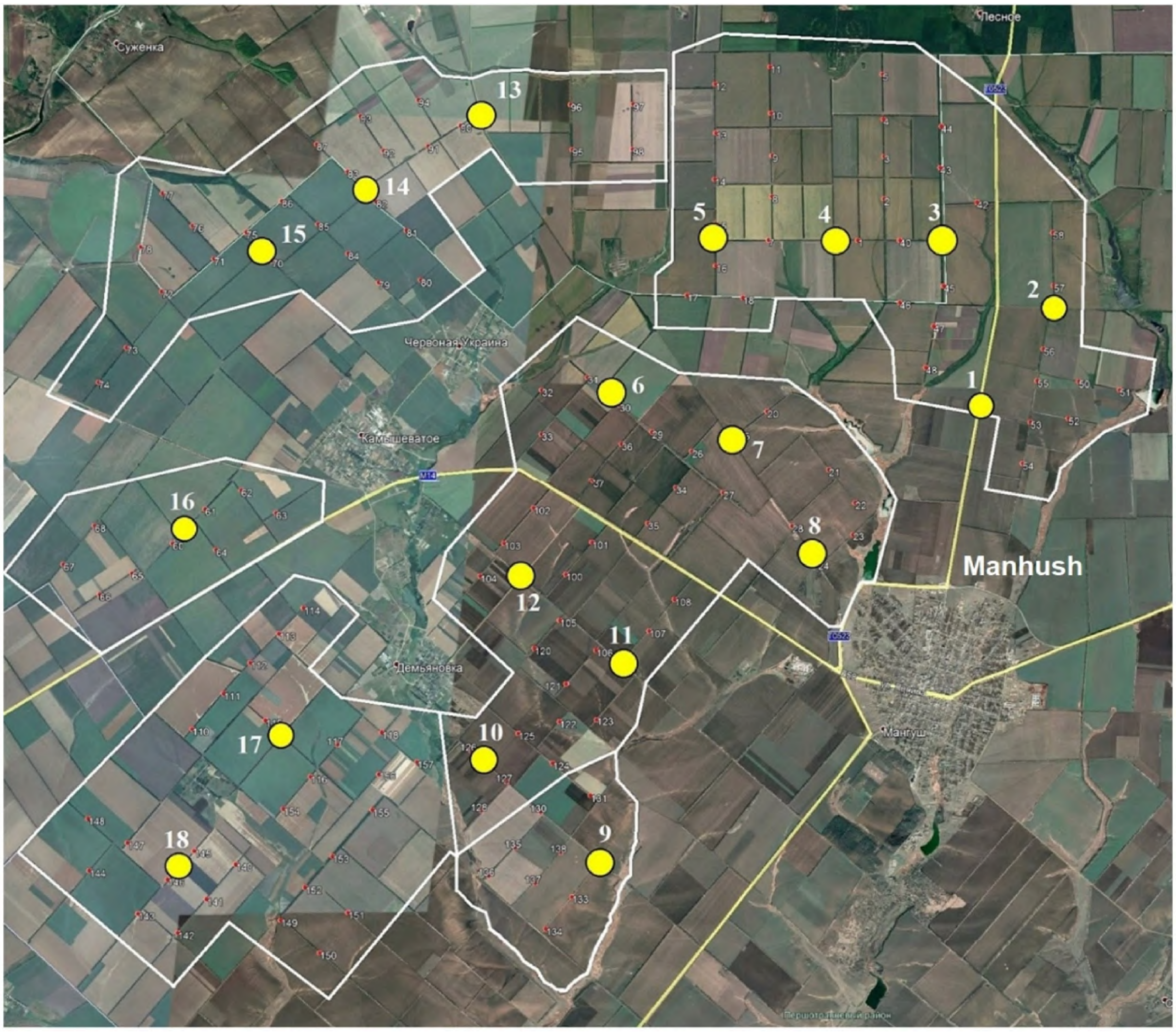

Figure 1. Location of bat detector vantage points within the Wind Farm LLC wind park (a white line – wind farm boundaries; grey circle is a wind turbine generator (WTG); white circle are the bat detector vantage points).

2.2. Duration and survey methods

Detector monitoring of bat activity is carried out within one year from the moment when bats come out of hibernation (March) and until the cessation of autumn migration and search for winter roost sites (October-November).

Table 1. Characteristics of bat detector vantage points within the Wind Farm LLC wind park (number according to figure 1).

Number	Habitat	North	East
1	Farmland, forest belt, main road	47.1022	37.3121
2	Farmland, forest belt, dirt road	47.1204	37.3271
3	Farmland, forest belt, dirt road	47.1292	37.2994
4	Farmland, forest belt, dirt road	47.1273	37.2740
5	Farmland, forest belt, dirt road	47.1253	37.2466
6	Farmland, forest belt, dirt road	47.0999	37.2234
7	Farmland, forest belt, dirt road	47.0940	37.2551
8	Farmland, forest belt, dirt road	47.0763	37.2773
9	Farmland, forest belt, dirt road	47.0241	37.2347
10	Farmland, forest belt, dirt road	47.0389	37.2029
11	Farmland, forest belt, dirt road	47.0588	37.2294
12	Farmland, forest belt, dirt road	47.0712	37.2028
13	Farmland, forest belt, main road	47.1413	37.1878
14	Farmland, forest belt, dirt road	47.1275	37.1630
15	Farmland, forest belt, dirt road	47.1156	37.1403
16	Farmland, forest belt, dirt road	47.0688	37.1275
17	Farmland, forest belt, dirt road	47.0387	37.1570
18	Farmland, forest belt, dirt road	47.0159	37.1364
19	Settlement, seacoast	46.9507	37.2500

2.3. Main provisions of the methodological approaches
Determination of monitoring sites was carried out taking into account the main habitats presented within the wind farm. There were used ultrasound detectors. Surveys were carried out in the period shortly before sunset and for at least three hours after dark.

Three research methods were initiated: ultrasound detection in separate vantage points; ultrasound detection on transects: ultrasound detection at a stationary vantage point throughout the night.

To characterize the Bat fauna of the region, there were used retrospective data obtained both within the project area and in adjacent areas.

2.4. Main requirements for environmental safety of the local populations of bats
All surveys were carried out within the wind farm after coordination of the work schedule and basic methods with the land users. During surveys in all cases there were used headlamps with electric light. Duration of surveys did not exceed the time intervals established by the method. No catching was carried out during surveys. Number of researchers was 1-2 persons. Within the project study area there was not found any colony of bats and swarming sites for day rest or hibernation. During the study period certain individuals, roosts, potential habitats of bats were not adversely affected by.

Taking into account the peculiarities of behaviour and biology of certain species of bats, to determine the species composition, vocal activity and patterns of distribution of the Priazovie species, the results of research in the adjacent areas were analyzed, which correctly characterizes certain aspects of the existence of bats at the Wind Farm LLC wind park.

2.5. Method 1. Ultrasound detection in separate survey vantage points

The study of territorial distribution, species composition, migration activity of bats was carried out according to generally accepted methods, using mainly their remote component. The studies were performed when bats were coming out of hibernation, during seasonal migrations and in the breeding season. In the twilight, as far as the lighting allowed, visual observations were made, and as darkness fell, there was used a "Pettersson D 240x" ultrasound detector. While driving, certain vantage points were detected counting the number of bat signals received for 10 minutes and capturing geographical coordinates with the "GARMIN GPSMAP 78s" navigator for their further processing in the Google Earth computer program. The signals of bats were recorded with a "ZOOM HandyRecorder H2" digital device.

The spatial distribution and flying activity of bats within the wind farm and buffer zones were determined at 18 vantage points counting the number of signals perceived by the ultrasound detector for 10 minutes of detecting (table 1; figure 1).

All 18 vantage points are located within the wind farm in places with the highest density of future wind turbines in accordance with the planning scheme. To compare the results of the research, the vantage point number 19 was located in the village of Nova Yalta.

Thus, the total number of vantage points, the information from which we used to characterize the activity of bats, is sufficient to objectively assess the status of chiroptera complexes of the project area. Driving the car from point to point, the visual observation, as far as the lighting allowed, has been carried out. This further characterized the altitudes and flight directions of the animals.

2.6. Method 2. Ultrasound detection on transects

Taking into account the recommendations of "Surveillance and Monitoring Methods for European Bats Guidelines produced by the Agreement on the Conservation of Populations of European Bats (EUROBATS)", as well as the example of carrying out similar surveys in Germany [4], 6 transects with a total length of 46 km were created within the Wind Farm LLC wind park (figure 2; table 2).

Table 2. Characteristics of transects within the Wind Farm LLC wind park.

Area	VP at a transect	Length, km	Approximate time of passage
1	1-8	21.0	1 hour 00 minutes
2	13-15	10.5	0 hours 30 minutes
3	11-12	3.5	0 hours 10 minutes
4	9-10	3.5	0 hours 10 minutes
5	16	3.0	0 hours 10 minutes
6	17-18	4.5	0 hours 15 minutes
Total	1-18	46 km	2 hours 15 minutes

Transects are located so as to cover the main habitats. Agricultural lands, which are divided into separate fields by forest belts, dominate within the Wind Farm LLC wind park. In the north-eastern and south-western parts of the wind farm there are ravine-beam systems in the relief and from the point of view of cracks, caves or underground roosts, these areas are not very attractive for bats, but can serve as forage places for animals. Among the transport infrastructure elements, there are two asphalt roads with medium load within the wind farm. High-voltage power transmission lines and a network of dirt roads also run through the territory.

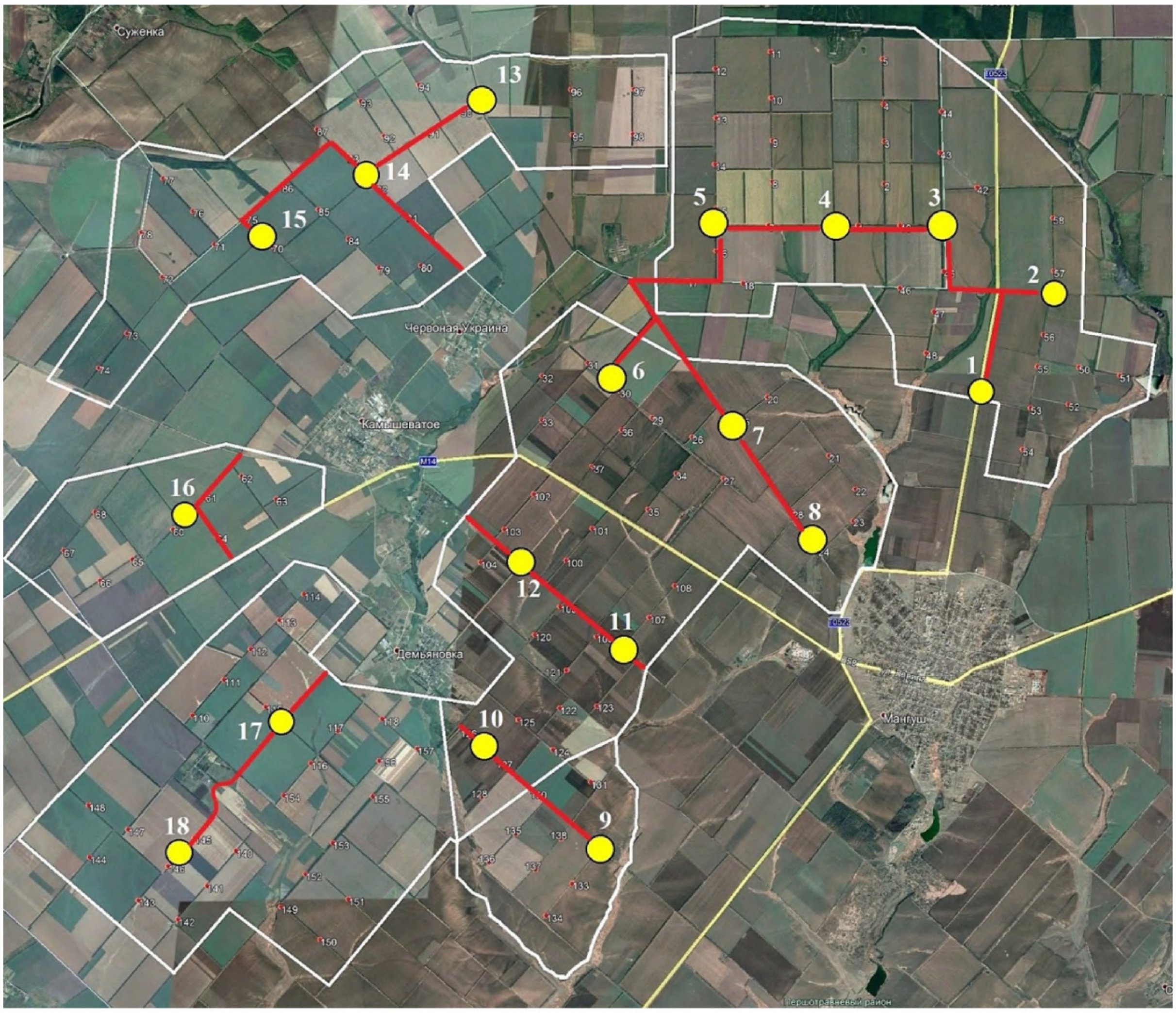

Figure 2. Location of transects (a double white line) for detection of the vocal activity of bats within the Wind Farm LLC wind park (a white line) in comparison with vantage points (1-18).

The main criteria for selecting transects. Taking into account the approximate standard of 1 km of transects for every 500 hectares of the project area, the transect of 46 km covers about 23.0 thousand hectares, which fully reflects the needs of research. Within this transect there are 18 vantage points, the distance between them is approximately the same. The frequency of detection is determined 10 times a year (1 – start of bat activity after hibernation; 3 – spring migration; 2 – breeding season; 1 – summer period; 2 – autumn migration; 1 – search for winter roost sites). When planning expeditions, favourable weather conditions for bat activity were taken into account.

According to the functional zones, each transect is 100% located within the wind farm.

2.7. Method 3. Ultrasound detection throughout the night at a stationary vantage point

There was also used the Pettersson D500x ultrasound detector, which was installed to determine the daily activity of bats on the wind farm territory not far from the planned location of the wind turbine generator № 130 (figure 3).

SAMP. FREQ. = 500
PRETRIG. = OFF
REC. LEN = 5
HP-FILTER =YES
AUTOREC = YES
T. SENSE = HIGH
INPUT GAIN =80
TRIG LEV=80
INTERVAL=5

Figure 3. Installation location of the Pettersson D500x ultrasound detector and its settings.

Working conditions. Detector installation height – 2.0 m. Parameter settings of the Pettersson D500X ultrasonic detector (figure 3). Duration of detection from 18:00 to 06:00. Frequency of detection – March (1), April (3), May (2), June (1), August (1), September (4), October (4), November (1); total 17 nights. Weather conditions did not interfere with the free behaviour of bats (no precipitation, strong winds, low temperatures).

2.8. Analysis of collected data

Data analysis was performed according to generally accepted methods of statistical, mathematical, tabular, graphical, cartographic and photographic processing using the following services: Microsoft Office Excel; Microsoft Office Word; Foxit Phantom; STATISTICA 8; Google Earth Pro; FastStone ImageViewer 4.9 Final.

2.9. Determination of bat activity indicators

It is a common international practice to carry out such studies to determine activity indicators in order to assess the possible impact of a project wind farm on bats objectively.

Based on the results, the activity index for all bats is determined using the following formula:

$$I_x = N_x \cdot 60/T,$$

where: I_x – activity indicator for the species or group of echolocation “x”; N_x – number of bat flights of the species or group of echolocation “x” observed during registration at the vantage point / transect (or during all registrations taken into account); T – total duration of the analyzed registration at the vantage point / transect (or all registrations taken into account), indicated in minutes.

Such calculations make it possible to characterize the periods of minimum and maximum activity of bats for further action and measures for the management of natural environmental complexes.

3. Results

3.1. Research at vantage points (Method № 1)

During expedition trips to the project area from September 2019 to August 2020, 18 detections were carried out at separate vantage points. Detailed characteristics of the obtained field data are given in table 3.

Table 3. Characteristics of the intensity of bat signals in 2019-2020 at the vantage points of the Wind Farm LLC wind park.

VP	T, 2019	N, 2019	I_x, 2019	T, 2020	N, 2020	I_x, 2020	T, 2019-2020	N, 2019-2020	I_x, 2019-2020
1	99	15	9.09	111	5	2.70	210	20	5.90
2	95	24	15.16	90	11	7.33	185	35	11.25
3	91	11	7.25	90	9	6.00	181	20	6.63
4	95	19	12.00	93	2	1.29	188	21	6.65
5	100	20	12.00	94	2	1.28	194	22	6.64
6	90	13	8.67	90	5	3.33	180	18	6.00
7	91	6	3.96	90	4	2.67	181	10	3.32
8	90	11	7.33	93	22	14.19	183	33	10.76
9	92	13	8.48	92	7	4.57	184	20	6.53
10	91	10	6.59	96	21	13.13	187	31	9.86
11	90	9	6.00	90	3	2.00	180	12	4.00
12	91	6	3.96	95	6	3.79	186	12	3.88
13	91	4	2.64	81	4	2.96	172	8	2.80
14	95	2	1.26	80	4	3.00	175	6	2.13
15	93	6	3.87	80	2	1.50	173	8	2.69
16	91	6	3.96	80	5	3.75	171	11	3.86
17	93	5	3.23	82	8	5.85	175	13	4.54
18	98	3	1.84	87	7	4.83	185	10	3.34
19	94	7	4.47	92	46	30.00	186	53	17.24
Total	1770	190	6.44	1706	173	6.08	3476	363	6.21

Notes: T – survey duration, min; N – number of registered signals; I_x – index of bat activity (see the Method). ND – (no detection) surveys were not carried out due to a sharp drop in temperature and lack of animal activity.

Thus, in 2019, 190 signals were received at vantage points, and in 2020 – 173. To determine the role of separate vantage points, we'll analyze the number of registered signals at each of them. We will remind that VPs 1-18 are located within the project wind park, and VP 19 is in the village of Yalta (Donetsk region, Ukraine). As we can see from the results of surveys (table 3 and figure 4), in 2019-2020 the total number of recorded signals of bats was in the range of 6-35, on average 17.22 signals for a vantage point. At five points the total number of signals was less than 10, at 8 VPs it reached 11-20 signals, two points showed a result of 21 and 22 signals and 3 VPs had more than 30 signals. The vantage points that gained maximum values were located as follows. VP 2 was next to the wind turbine generator 57, VP 8 – between the WTG 28 and the WTG 24 (in the north of Manhush and not far from the pond), and VP 10 – next to the WTG 126 near the village of Demianivka. In our opinion and according to the results of previous studies in the Azov-Black Sea region, such a relatively high activity of animals is associated with the close location of the water area and settlements where bats have the opportunity to rest and forage in the lighted areas. This assumption is confirmed by the results of detection at VP 19 near the village of Yalta, where in total 53 signals were registered.

One of the indicators of animal behaviour is the activity index, which characterizes the theoretical possibility of registering bats over a period of time. Figure 4 shows how the values of this index change at separate vantage points. However, international practice focuses on the

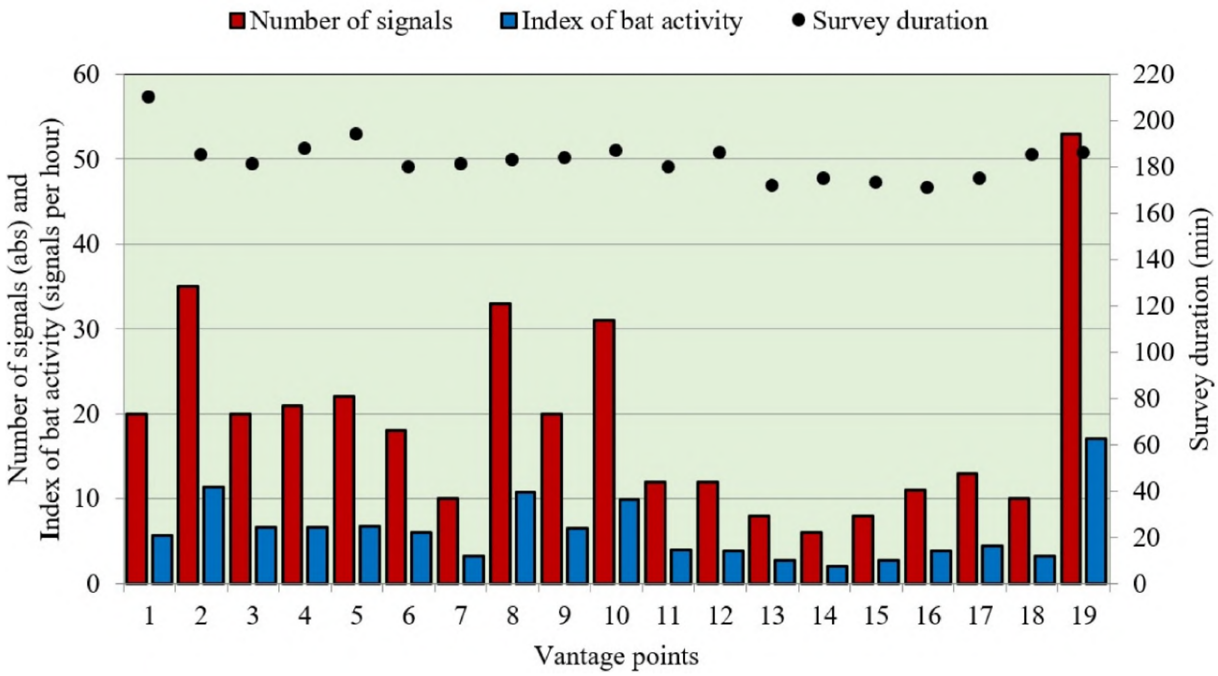

Figure 4. The ratio of the survey duration to the number of signals and the index of bat activity at the vantage points of the Wind Farm LLC wind park in autumn 2019 and in 2020.

Table 4. Monthly dynamics of vocal activity of bats at the vantage points of the Wind Farm LLC wind park in autumn 2019 and in 2020.

Year	Month	Duration, min	N	Activity index, I_x
2019	September	801	142	10.64
2019	October	779	45	3.47
2019	November	190	3	0.95
2020	March	124	0	0.0
2020	April	584	33	3.39
2020	May	405	42	6.22
2020	June	198	27	8.18
2020	August	395	71	10.78
2019-2020	Total	3476	363	M = 6.27

monthly dynamics of the bat activity index, which we calculated in table 4.

As we can see from table 4, the activity of animals, depending on the phenological phase of their annual cycle, ranged from 0 signals per hour up to 10.78 signals per hour. Such indicators are quite typical for the region and indicate the absence of natural and anthropogenic conditions for increased activity of bats within the wind farm. The maximum activity of animals was registered in August (10.78 signals per hour) and in September (10.64 signals per hour), which is also traditional for bats, as it is during this period that the first migratory movements and peak migrations for some species take place. The complete absence of signals at vantage points in March, when nighttime temperatures drop sharply in relation to daytime temperatures, is a fairly expected picture, in contrast to the relatively low values of the activity index in April –

only 3.39 signals per hour. This can be explained by fluctuations in air temperature and atypical weather conditions (at night in the second half of April, air temperatures dropped to + 3-4°C). Surveys in May and June revealed no differences from the average annual bat activity indicators in the region.

3.2. Vocal activity of bats on transects (Method № 2)

The study of vocal activity of bats on transects was carried out during 12 expedition trips in the period from November 2019 to August 2020. A total of 104 signals of bats were recorded. The amplitude of vocal activity indicators within a single transect ranged from 0 to 10 sounds.

The characteristics of the vocal activity of bats during different phases of the life cycle indicate the absence of periods of unconditional dominance. Thus, on April 13-14, 2020, a maximum of 20 signals was recorded on transects, and 10 of them were registered on the transect №1. This is not a very typical picture, as according to our retrospective data in the region in mid-April, activity indicators are not maximum. Instead, in May the activity of animals has always been high, but within the transects in the project area we can see a rather unusual picture when at night of May, 11-12, 18 signals were recorded, and the next night of May, 12-13, only 11.

The lack of results during the research in March and November is expected, because during these periods bats are not very active and located near winter roosts, which are situated more often than other places in the settlements, outside the transects. A more detailed description of the summary results of research on transects is shown in tables 5-6.

Table 5. Dynamics of vocal activity of bats (signals) on transects (T1-T6) of the Wind Farm LLC wind park in autumn 2019 and in 2020.

Date	T1	T2	T3	T4	T5	T6	abs.	%
11-12.09.2019	5	3	1	1	1	1	12	11.54
19-20.09.2019	4	1	0	0	0	0	5	4.81
11-12.10.2019	6	1	0	0	0	0	7	6.73
18-19.10.2019	0	0	0	0	0	1	1	0.96
12-13.11.2019	0	0	0	0	0	0	0	0.00
13-14.03.2020	0	0	0	0	0	0	0	0.00
13-14.04.2020	10	3	2	1	2	2	20	19.23
22-23.04.2020	2	0	0	0	0	0	2	1.92
11-12.05.2020	6	1	2	4	0	5	18	17.31
12-13.05.2020	6	1	0	1	1	2	11	10.58
08-09.06.2020	6	3	2	1	0	2	14	13.46
15-16.08.2020	6	2	2	1	1	2	14	13.46
Total. abs.	51	15	9	9	5	15	104	100.0
mr Total. %	49.04	14.42	8.65	8.65	4.81	14.42	100.0	

Using the methodology of research on transects, data on the activity of animals in settlements and at crossings between transects were additionally obtained. The LunaBAT DFR-1 PRO ultrasound detector did not turn off during the entire route, and the capabilities of the built-in GPS module allowed to “tie” each signal to the terrain. Thus, table 6 presents the results of research obtained not only on transects but also in adjacent areas.

As we can see from table 6, the number of signals recorded in the settlements (Manhush, Demianivka, Komyshuvate) is equal to 60, which is a high indicator compared to the short travel time of these settlements. During the crossings between the transects, 73 signals were

Table 6. Vocal activity of bats (signals) during research on transects of the Wind Farm LLC wind park in autumn 2019 and in 2020.

Date	Transects	Settlements	Crossings between transects	abs.	%
11-12.09.2019	12	13	9	34	14.35
19-20.09.2019	5	7	7	19	8.02
11-12.10.2019	7	2	4	13	5.49
18-19.10.2019	1	4	0	5	2.11
12-13.11.2019	0	0	2	2	0.84
13-14.03.2020	0	1	0	1	0.42
13-14.04.2020	20	6	2	28	11.81
22-23.04.2020	2	1	1	4	1.69
11-12.05.2020	18	6	4	28	11.81
12-13.05.2020	11	2	13	26	10.97
08-09.06.2020	14	6	15	35	14.77
15-16.08.2020	14	12	16	42	17.72
Total, abs.	104	60	73	237	100.0
Total, %	43.88	25.32	30.80	100.0	

received, which also indicates the high activity of bats, but this is due to the presence of two large water bodies along which the expedition car was moving at a low speed. It is above the waters of these reservoirs that bats find a satisfactory forage base.

To reflect the level of activity of bats within the transects, we use not only absolute values, but also the calculated index of activity, which takes into account the detection time. Table 7 presents the results of such calculations. We can see that despite the largest absolute number of signals within the transect № 1 (51 signals), the activity index here is equal to 4.25 signals per hour, which is considered the average result. Within the transects № 2 and № 5, the activity of animals is the lowest – 2.5 signals per hour. A total of only 15 signals were recorded on the transect № 6 during the research period, which gives us a result of 5.0 signals per hour taking into account the transect length and the duration of detection. Although this is the highest indicator of bat activity on all transects, these values are average in terms of the possible negative impact of wind turbines on animal populations.

Speaking of the average calculated indicator of vocal activity of bats, we state that for a 46-kilometer total transect within the Wind Farm LLC wind park, 3.85 signals can be recorded per hour of detecting, which is considered to be a low number of animals.

3.3. Surveys at a stationary vantage point (Method № 3)

The method of obtaining additional information is to survey at a stationary vantage point throughout the night using the Pettersson D500x ultrasound detector. Such studies primarily provide information on the species composition of bats and their daily activity. In previous years, such studies have given us a complete list of bat species in the Azov-Black Sea region. Moreover, we have consolidated results from the territories of the Prymorsk wind farm (2 years), the Botiievo wind farm (7 years), the Orlovka wind farm (2 years), the Prymorsk wind farm-2 (2 years), the town of Melitopol (5 years), the village of Stepanovka-Persha (fragmentary), the Obytichna Spit (fragmentary). Comparison of the species composition allows us to state a fairly stable list of species, so it is absolutely correct to use such consolidated regional data to characterize the species composition and vocal activity of bats for any area of the Pryazovie region.

For example, the stationary Pettersson D500x ultrasound detector has been recording the signals of bats in automatic mode from 18: 00 to 06: 00 (for 720 minutes). A total of 14 surveys were carried out (6 in 2019 and 8 in 2020).

Analyzing data presented in tables 8-9, we state that the activity of bats in their seasonal dynamics was rather unstable. Thus, in March and November the lowest rates are traditional, but behaviour of bats in April was extremely contrast. Even within neighbouring nights of the detection we can see that in April, 13-14, 106 signals were registered, and the next night under the same weather conditions there were only 6 signals. Sharp cooling in the second part of April affected the results of the detection when on the night of April, 22-23, the device recorded only one signal. Since May, the activity of animals was traditional for the region showing maximum values in September, 2019 and August, 2020.

Surveys during all night allow to give characteristics of a daily behaviour of animals and define periods of the highest activity and periods of attenuation.

Table 8 presents data regarding moments of the first and the last registration of bats according to the duration of activity and shows the time of the median of signals (50 % of their total).

Analysis of tabular data (table 8) shows that half of the sounds heard throughout the night was recorded before 24:00, and on colder nights (March, first half of April, October and November) bats are active only during 2-3 hours, then their vocal activity decreases sharply. In August and September, the duration of the period of animal activity is the largest (more than 8 hours), but the peak of this activity is at the first 2.5-3.5 hours. Such calculations are the basis for specific well-grounded recommendations to minimize the possible negative impact of operating wind turbines and the basis for environmental management measures.

4. Species diversity of bats

To obtain information on the species composition of bats that occur in different seasons within the Wind Farm LLC wind park, three methods of data collection were used: ultrasound detection on transects, detection at vantage points and a stationary method of detecting automatically with a detector throughout the night. To these data there were added the signals obtained as a result of their recording in settlements (accidental counts), during crossings between transects and vantage points. A total of 1687 signals were obtained, 1235 of which were identified to the species, using the most modern techniques [5]. Characteristics of counts, the number of signals of certain species and their dynamics in 2019–2020 are shown in figure 5.

The species diversity of bats on the territory of the Wind Farm LLC wind park in autumn

Table 7. Index of vocal activity of bats on transects of the Wind Farm LLC wind park in autumn 2019 and in 2020.

Transect	Number of signals	Length, km	Duration of a survey, min	Number of surveys	Total survey time, min	Activity index, I_x
1	51	21.0	60	12	720	4.25
2	15	10.5	30	12	360	2.50
3	9	3.5	10	12	120	4.50
4	9	3.5	10	12	120	4.50
5	5	3.0	10	12	120	2.50
6	15	4.5	15	12	180	5.00
Total	104	46	135	72	1620	3.85

Table 8. Activity of bats in autumn 2019 and in 2020 at the Wind Farm LLC wind park according to the results of the ultrasound detection at a stationary vantage point.

Date	*N*	Survey duration, min	First registration	Last registration	Activity duration	Median
11-12.09.2019	107	720	20:01	03:53	07:52	22:41
19-20.09.2019	120	720	20:20	05:51	09:31	22:52
20-21.09.2019	155	720	22:00	04:53	06:53	22:53
11-12.10.2019	70	720	19:12	01:33	06:21	19:41
18-19.10.2019	5	720	19:23	03:27	08:04	19:51
12-13.11.2019	23	720	17:00	02:10	09:10	17:55
13-14.03.2020	2	720	18:56	19:08	00:12	–
13-14.04.2020	106	720	19:50	01:57	06:07	20:32
14-15.04.2020	6	720	21:35	02:47	05:12	22:50
22-23.04.2020	1	720	21:30	21:30	00:01	–
11-12.05.2020	115	720	20:48	02:28	05:40	23:53
12-13.05.2020	115	720	20:08	04:37	08:29	21:48
08-09.06.2020	95	720	21:34	02:01	04:27	23:12
15-16.08.2020	167	720	20:51	04:48	07:57	23:15
Total	1087	10080	17:00-22:00	01:33–05:51	6:11	21:47

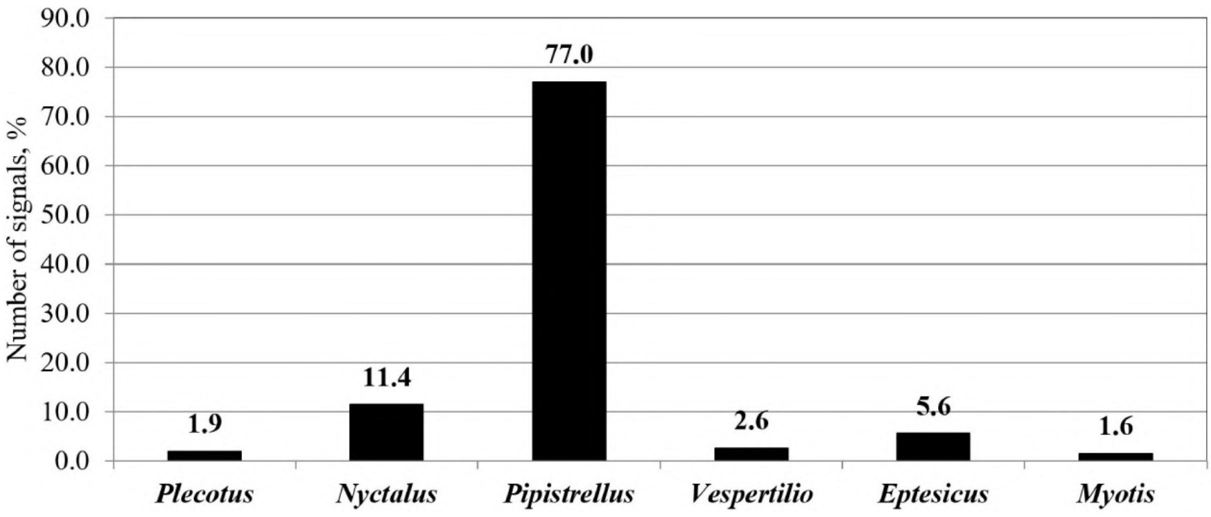

Figure 5. Species diversity of bats on the territory of the Wind Farm LLC wind park (taxonomic rank).

2019 and in 2020 is characterized by at least 10 species that belong to 6 taxonomic ranks. *Pipistrellus kuhlii*, the part of which was 61.1% of the whole complex, was the undisputed dominant. Within the group of *Pipistrellus*, there also were *Pipistrellus nathusii* (23 signals, 1.9%), *Pipistrellus pipistrellus* (28 signals, 2.3%) and *Pipistrellus pygmaeus* (3 signals, 0.2%). Bats, not identified to the species, from the group *Pipistrellus kuhlii – Pipistrellus nathusii* amounted to 10.4% (128 signals). Thus, we state that within the project area at least 4 species of *Pipistrellus* overall in 2019-2020 amounted to almost 77% of all registered signals.

The subdominant was *Nyctalus noctule* with 138 signals, or 11.2%. *Eptesicus serotinus* was

Table 9. Indicators of the bat activity index at a stationary vantage point within the project area of the Wind Farm LLC wind park.

N	Date	Number of signals	Night duration*, min	Activity index, I_x	Activity duration**, min	Activity index, I_x
1	11-12.09	107	612	10.49	472	13.60
2	19-20.09	120	639	11.27	571	12.61
3	20-21.09	155	642	14.49	413	22.52
4	11-12.10	70	711	5.91	381	11.02
5	18-19.10	5	734	0.41	484	0.62
6	12-13.11	23	805	1.71	550	2.51
7	13-14.03	2	671	0.18	12	10.00
8	13-14.04	106	565	11.26	367	17.33
9	14-15.04	6	562	0.64	312	1.15
10	22-23.04	1	534	0.11	1	–
11	11-12.05	115	475	14.53	340	20.29
12	12-13.05	115	472	14.62	509	13.56
13	08-09.06	95	415	12.3	267	19.1
14	15-16.08	167	521	19.23	477	21.01
Total	abs.	1087	415-805	0.11-19.23	1-571	0.62-22.52
Average	per night	77	597	8.37	368	12.7

Note: * – night duration is calculated according to the astronomical calendar as the interval between civil twilights; ** – activity duration is the interval between the first and last registration of bat signals.

recorded 68 times, which is 5.5% of the total. Other species were extremely rare and each of them did not score 3% of the total number of signals. This situation is typical for the entire south of Ukraine and the Sea of Azov region in particular [6].

In relation to all species of bats in Ukraine, the bats of the project area are less than 40%, which is a sign of relatively low species diversity.

5. Discussion

5.1. Assessment of the impacts caused by the construction and operation of the Wind Farm LLC wind park (800 MW) on bats in 2019-2020

To assess the possible impact of the wind farm during its construction, an important indicator is the index of animal activity at the project area. Tables 3-9 show the results of such calculations. As we can see, the index of bat activity calculated from the results of surveys at separate vantage points, at the stationary vantage points and within the transects was quite diverse.

Thus, with a time-limited study of the vocal activity of bats (the first 4-5 hours after twilight) using detection methods at vantage points, the activity index on average was equal to 6.27 signals per hour (lim: 0.0-10.78). During the detection on transects, this indicator was slightly lower – 3.85 signals per hour. A possible explanation for this is the presence of repeated sounds of one individual in the records of signals for 10 minutes of the detection in one place, which is almost impossible to assume when recording signals, constantly moving in the car across transects.

Stationary detections throughout the night gave a little more importance, but we should take into account some features of such calculations. Table 9 shows the results of the vocal activity of animals taking into account the time interval between the first and last registration of bats (period of activity) on the one hand, and the night duration (interval between evening and morning twilight) on the other hand. In our opinion, the latter index is more indicative, as it theoretically includes periods when bats are active but were not in the coverage area of the detector. Thus, using the method of the stationary detection, we obtained the activity index which amounted to 12.65 signals per hour for the period of activity, and 7.80 signals per hour for the dark period of the day (per night).

The estimated total activity index, taking into account the results of three research methods, was 6.93 signals per hour, which characterizes the project area as the average attractiveness for bats (table 10).

Table 10. Estimated total index of bat activity on the territory of the Wind Farm LLC wind park in autumn 2019 and in 2020.

Month	Total signals	Survey duration, min	I_x VP	I_x Transect	I_x Stationary VP	Average I_x
March	2	930	0.0	0.00	0.18	0.13
April	168	2515	3.39	4.89	4.08	4.01
May	301	1622	6.22	6.44	14.57	11.13
June	136	748	8.18	6.22	13.73	10.91
August	252	1051	10.78	6.22	19.23	14.39
September	541	2964	10.64	3.78	12.11	10.95
October	128	2494	3.47	1.78	3.11	3.08
November	26	1130	0.95	0.00	1.71	1.38
Total	1554	13454	6.27	3.85	7.80	6.93

5.2. Research area zoning in terms of bat sound density

To obtain more specific information on the territorial distribution of bats in the project area, we used the Kernel Density method for point objects. The result of applying this technique is the construction of zones of increased activity of bats, both in certain periods and for all observation seasons, on a cartographic basis.

Such zoning allows to identify places of potential risk for bats and to provide appropriate recommendations on environmental management and minimization of impacts. The Kernel Density method was described by us in previous articles [7–9].

5.3. Characteristics of the functional zones of the Wind Farm LLC wind park (800 MW)

5.3.1. The period of leaving winter roosts by animals (13-14.03.2020). In total, only one signal was registered in the vicinity of Manhush, an urban-type settlement. Bats were not registered within the wind farm, which may indicate the absence of conditions for wintering animals. According to our surveys, the activity of bats in this period depends on weather conditions. In the Azov-Black Sea region in all the areas where research has been carried out during the last 10 years, the activity of animals was minimal. The forage base for bats in this period was also depleted. We state that during the period when the animals leave their winter roosts, no negative impact of the operating wind farm is expected on them.

5.3.2. The period of the spring migration and the formation of breeding colonies (13-14.03 – 13-14.04.2020). The increase in the number of signals, as an indicator of the activity of bats, occurred in the next phenological period after the March studies – the spring migration and the formation of breeding colonies. There were obtained a total of 29 signals, which were unevenly distributed throughout the project area. Thus, 20 signals were recorded on transects within the wind farm, 6 signals in settlements and 2 signals in adjacent areas.

The highest density of signals was obtained in the following areas: 1) between the wind turbine generators № 45, 47 and 57; there is a small beam system with wet areas, which presumably attract bats; 2) northeast of the village of Ukrainka, where the nearest wind turbine generator № 17 is located at a sufficient distance to reduce the negative impact; 3) in the vicinity of the village of Manhush near the pond with a large area of open water; the nearest wind turbine generator is № 24 which is in the zone of increased signal density.

5.3.3. The period of reproduction and the peak activity of local bat populations (22.04-13.05.2020). During this period, 58 signals were recorded. Analysis of the distribution of bats and identification of areas of high signal density show us the following picture:

- the village of Demianivka and the forest in its vicinity, this zone includes the wind turbine generators № 118, 125, 126 and 157;
- with a lower density of points is the next zone which includes the branch of the village of Demianivka (southwest); no wind turbine generator entered this area;
- within the transect № 1 between the vantage points № 2 and № 3 in the wet descent there is a zone of medium density, which includes the wind turbine generators № 45 and 47.

5.3.4. The period of summer flights (08-09.06.2020). During this period, we have information about 35 signals, 14 of which were registered on transects within the wind farm. The rest of them were in the settlements and during crossings between transects. This number of signals allows to outline zones of high density of bats:

- the village of Demyanivka and its vicinity close to the wind turbine generator № 126; the wind turbine generators № 157 and 118 are also in the zone of impact;
- the vicinity of the village of Manhush near the pond with a large area of open water; the nearest wind turbine generator is № 24 which is in the zone of increased signal density.

5.3.5. The period of the disintegration of colonies, the beginning of autumn migrations and grouping in flocks (15-16.08.2020). The maximum indicators of the vocal activity were obtained during the beginning of autumn migrations – 42 signals. Analysis of the registration points of these signals allows us to show the areas of the wind farm with the highest density:

- the zone of maximum density is located northwest of the village of Manhush; the wind turbine generators № 21, 22, 23, 24, 27 and 28 are in this zone;
- the medium density zones are located on the transect № 1 (wind turbine generators № 17 and 34), the transect № 4 (wind turbine generators № 126, 127 and 130) and near the village of Demianivka (outside the wind farm and transects).

5.3.6. The period of autumn migrations and grouping in flocks (11.09 – 19.10.2019). 71 signal recorded in this period showed that the greatest density is located in the following locations:

- the vicinity of the village of Manhush, wind turbine generators № 23, 24 and 28;
- the village of Demianivka and the forest in its southern vicinity; wind turbine generators are absent.

5.3.7. The period of the last flights between roosts and the beginning of hibernation (12-13.11.2019). The decrease in the activity of bats during this period led to accidental registrations of animals. We operate with only 2 signals that did not have places of high density. Both signals were recorded outside the wind farm on the Yalta-Manhush highway. Thus, the activity of the wind farm during this period will not have a negative impact on bats.

5.3.8. Analysis of the density for the entire study period (September, 2019 – August, 2020). Thus, applying the Kernel Density technique, we will show the zones of maximum indicators of bat activity within the project area. Figure 6 shows these areas.

Most bats were registered in the north-western vicinity of the village of Manhush where the transect № 1 partially passes, and there is a large pond too. This zone can also be divided into areas (subzones) with different levels of impact on bats. The red, most dangerous subzone includes wind turbine generators № 23 and 24. The lower risk subzone (orange) includes wind turbine generators № 22 and 28. The yellow and green subzones are not endangered for animals.

The next thickening of bat registration points is located near the wind turbine generators № 45 and 47 (the transect № 1).

Also within the transect № 1 between VPs № 5 and 6 there is another accumulation of bat registration points, but this zone lies outside the wind farm and none of the wind turbine generators is planned to be installed here.

In the village of Demyanivka and around it there was another zone of average frequency of bat counts. There is only one wind turbine generator № 126, the rest of the turbines are at a safe distance.

The least risk zone is located at the beginning of the transect № 4, near the Yalta-Manhush highway. Bats were found here quite regularly, but this area lies outside the wind farm. No wind turbine generator will be installed there either.

5.4. The impact of the Wind Farm LLC wind park on the life of bats

5.4.1. Impacts caused by the construction. The construction of the wind farm is carried out in a way that involves the location of the wind turbines in the forest belts. The quality of the forest belts within the project area in some places is quite high, so site clearing for separate wind turbine generators can have a negative impact on bats, dendrophiles.

1. *Emissions of harmful substances.* In the open environment the concentration of pollutants is not higher than in industrial centers with a high level of air pollution, where bats live permanently. In addition, during the construction emissions of harmful substances will not exceed the permissible norms due to the absence of stationary sources of pollution and a relatively short period of construction work. There is no negative impact on migrating bats.
2. *Deterrence by visual effects and noise.* Periods of daily activity of builders and bats may not coincide. Humans and bats coexist in large cities, where traffic does not stop around the clock. There are equally significant sources of noise in the surrounding areas (settlements, agricultural machinery, roads). Judging by the fact that we have registered animals everywhere, deterrence by visual effects is not threatening and the impact of these factors on resident bats and migrants is at least insignificant.
3. *Occupation of the territory by the working sites and equipment.* There is plenty of space on the working sites to avoid obstacles. In addition, the distribution of working sites and equipment is insignificant and does not interfere with forage flights of the bats because of the great wind farm area and and big distances between the wind turbine generators (up to 500 m). Negative impact on bats from temporary placement of equipment is absent.
4. *Loss of breeding sites.* The roosts of bats, where they spend the day and breed, are usually located in settlements and farm buildings among the agrocenosis. If the buildings are

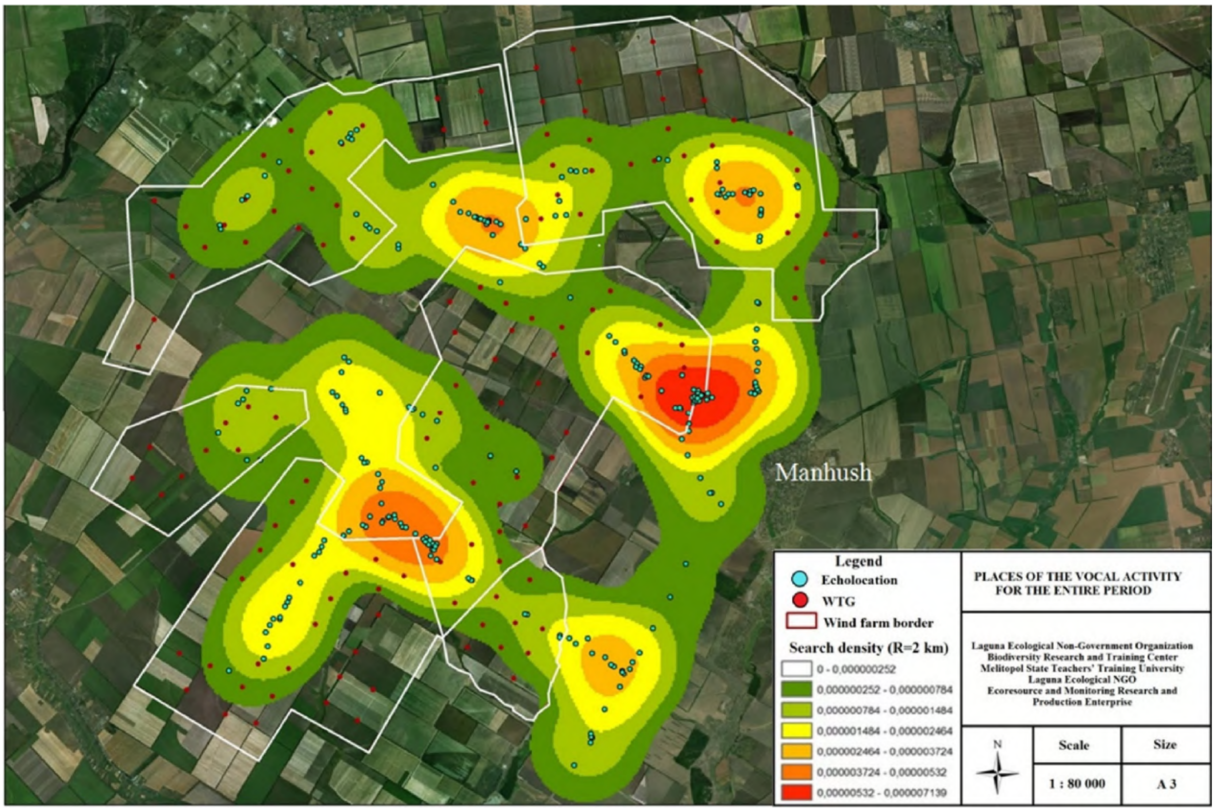

Figure 6. Kernel Density of count points of bats within the Wind Farm LLC wind park in autumn 2019 and in 2020 (12 expedition trips; 237 signals).

not subject to liquidation during the construction process, the breeding sites are not lost. Certain risks of loss of breeding sites exist for bats of the dendrophile group (Pipistrellus), when areas of forest belts will be cut down to install some wind turbine generators. This phenomenon is mosaic in nature, continuous deforestation is absent in the project, so for most bats there is an opportunity to find alternative forest belts for breeding. It is for this group of bats during the breeding period that the risk of negative impact is assessed as medium, and it is absent during the periods of migration and hibernation.

5. *Loss of individuals of certain species.* The space on the sites is quite enough to bypass the obstacles by the animals that have echolocation. As a rule, forage migrations were registered at altitudes not exceeding 20 m and this altitude interval is safe for bats. Migrants are represented by widespread species and the loss of individuals, which in one way or another occurs in nature, will not lead to a critical status of populations as a whole. The negative impact on migrating bats is characterized as low. Thus, the impact on bats during the construction of the wind farm is from medium to minimal, and after this short period it is absent.

5.4.2. Impacts caused by equipment

1. *Long occupation of the territory and change of characteristics of the territory.* Among the equipment used in the construction of the wind farm and its infrastructure, heavy machinery (trucks, tractors, cranes, etc.), cars, and storage of construction materials can impact on bats. These types of work are accompanied by the formation of large amounts of dust, which

can be an obstacle for bats if the work is carried out at night. According to our surveys, the night work at the already built megawatt-class wind farms lasted a short period of time and was limited to small sites. Thus, the negative impact on bats during foraging had signs of medium level, and for breeding individuals it was insignificant.

2. *Deterrence by mast vertical structures.* A high-voltage power transmission line runs near the wind farm. Visual and detective surveys did not reveal a negative impact on migrating bats from both vertical structures (supports) and horizontal ones (electric wires). The influence of dense power transmission lines in settlements, which are the main habitats of bats, has not been recorded either. There is enough space on the wind farm and in the buffer zones to bypass the barriers by animals that have echolocation and are easy to maneuver amid obstacles. There is no negative impact on bats that make forage and migration flights.
3. *Barrier effect and obstacles for flight.* Bats do not have a well-established narrow forage migratory corridor, their movements depend more on a satisfactory forage base (insects), which, in turn, is directly related to crop rotations in agrocenoses. There is a certain element of a chaotic movement of bats through the wind farm. The distance between the wind turbine generators is from 550 meters and more, and does not constitute any barrier effect for small animals, like bats, which have echolocation and are easy to maneuver even in forests. Obstacles to the flight from the construction of the power transmission line are also minimal, as the power transmission lines of different capacities are laid throughout the region, and no negative impact on the bat population has been established.

The negative impact on bats is low, and during their reproductive cycles it is absent.

5.4.3. Impacts caused by the operation of the wind farm (at the level of forecasts)

1. *Deterrence due to the rotor movement, flickering shadows, glare of light.* The analysis of researches shows that the altitude interval within the wind farm during the forage flights for the vast majority of bats does not exceed 20 m. Deterrence due to the rotor movement, flickering shadows and glare of light according to our surveys are not recorded. Thus, the negative impact due to the rotor movement, flickering shadows, glare of light effects is estimated to be low. The effect of these factors require further study, but surveys show that they are characterized as low and this is due to the small number and vocal activity of bats during the main reproductive cycles.
2. *Additional development of the territory.* Potentially, bats can use various niches in the wind farm structures and technical constructions for day roosts. The negative impact on bats is estimated to be low.
3. *Disturbance due to the night illumination.* Bats, on the one hand, avoid light and, on the other hand, hunt near lanterns which attract insects with their light. Within the wind farm, night illumination is localized at amplifying stations, offices and other infrastructure buildings, as well as at the wind turbine generators (at altitudes above 100 m). In the settlements it is proved that near the illuminated areas the vocal activity of bats is higher than near the unlit ones. Disturbance due to night illumination is unknown. The negative impact on bats is low.
4. *Collision with wind turbine generators.* The low number of bats in the local group, insignificant forage movements on the territory of the wind farm, the lack of transit migration routes give grounds to assess the impact of this factor as low. However, according to the literature, cases of collisions of bats with wind turbine generators are known for the entire species spectrum of animals encountered in the study area, and this makes them potentially dangerous animals. After the commissioning of the wind farm, the effect of this factor should be studied additionally. The probability of collisions of bats with wind turbine generators is prognostically left at the average level of danger.

6. Conclusion

Thus, a comparison of the data obtained in autumn 2019 and in 2020 concerning the study of foraging behaviour and vocal activity of bats allows us to draw the following conclusions:

1. The total number of registered voices is 1554 signals, 695 of which are recorded in 2019 and 859 in 2020.
2. Index of bat activity depending on the research methodology ranged in the interval 3.85 (on transects) – 7.80 (at a stationary vantage point), and was in average 6.93 signals per hour (for comparison: Myrne wind farm (the Kherson region) – 7.14 signals per hour; Kalanchak wind farm (the Kherson region) – 6.62 signals per hour; Overianivka and Novotroitsk wind farms (the Kherson region) – 10.53 signals per hour; Prymorsk wind farm (the Zaporizhzhia region) – 7.07 signals per hour; Prymorsk-2 wind farm (the Zaporizhzhia region) – 8.10 signals per hour; Botiievo(the Zaporizhzhia region) – 6.70 signals per hour; Zaporizhzhia wind farm (the Zaporizhzhia region) – 8.30 signals per hour).
3. Forage and migratory behaviour of bats, calculated by determining the index of their activity, shows the average values.
4. The distribution of bats in the project area, defined as the difference between the number of recorded signals in individual habitats, indicates the attraction of animals to settlements and open waters, while the wind farm area is less attractive to them.
5. The species composition of bats, identified for 1235 signals registered in the territory of the projected wind farm, is stable and represented by widespread at least 10 species belonging to 6 taxonomic ranks. The undisputed dominant was Pipistrellus kuhlii, the part of which was 61.1% of the whole complex. According to the Eurobat commission, this species is in the group with a low risk of collisions with wind turbine generators, while Nyctalus noctula with 138 signals, or 11.2% of the whole bat complex, has a high risk of falling under a moving rotor.
6. There are no species of the category “endangered” among the identified bats. The distribution areas of all species of the project area are quite wide. Within the Wind Farm LLC wind park there are no endemic species or unique habitats of their existence.
7. Analysis of the bat distribution, carried out by the Kernel Density method, revealed several areas of the increased activity of animals. Most bats were attracted to the settlements (Manhush, Demianivka, Ukrainka) and to open waters. There were revealed some wind turbine generators near which the implementation of minimization measures is required. In total, according to forecasts, there are 10-16 such wind turbine generators within the Wind Farm LLC wind park 800 MW.

We state that the construction and operation of the Wind Farm LLC wind park at the level of objective forecasts will not have a negative impact on the bat populations of the study area.

Monitoring the state of bats in the project area both during the construction of the wind farm and its operation is mandatory for the development and implementation of measures to minimize the possible negative impact on bats.

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References

[1] Battersby J 2017 *Guidelines for Surveillance and Monitoring Methods for European Bats* 3rd ed (*EUROBATS Publication Series* vol 5) (Bonn, Germany: UNEP / EUROBATS Secretariat) URL https://www.eurobats.org/sites/default/files/documents/publications/publication_series/EUROBATS_PublSer_No5_3rd_edition.pdf

[2] Masing M 2020 Study on bats (Chiroptera) in Berlin in 2019. Part 1. Detector-based study on bats in Berlin with the aim of monitoring their populations Tech. rep. Stiftung Naturschutz Berlin Berlin URL https://drive.google.com/file/d/1snWFuwS4EBOYIJOmATn-7yqFuiBDDtGL/view
[3] Zagorodniuk I, Godlevska L, Tyshchenko V and Petrushenko Y 2002 *Bats of Ukraine and adjacent countries: a guide for field investigations* (*Proceedings of the Theriological School* vol 3) (Kyiv) URL http://terioshkola.org.ua/ua/library/pts03-batguide.htm
[4] Dietz M and Simon M 2005 Säugetiere (Mammalia) *Methoden zur Erfassung von Arten der Anhänge IV und V der Fauna-Flora-Habitat-Richtlinie [Methods for detecting species of the Appendices IV and V of the Habitats Directive]* (*Naturschutz und Biologische Vielfalt* vol 20) ed Doerpinghaus A, Eichen C, Gunnermann H, Leopold P, Neukirchen M, Petermann J and Schröder E (Bonn: Bundesamt für Naturschutz) p 318–327
[5] Barataud M 2015 *Acoustic Ecology of European Bats Species Identification, Study of their Habitats and Foraging Behaviour* (*Collection Inventaires & Biodiversité* vol 16) (Paris: BIOTOPE)
[6] Volokh A, Gorlov P, Siokhin V, Polishchuk I and Motornyi D 2021 The State of the Fauna of Bats in the Ukrainian Azov Region in Modern Environmental Conditions *Proceedings of the International Forum on Climate Change and Sustainable Development: New Challenges of the Century, September, 9–11, 2021* (Mykolaiv: PMBSNU) URL https://core.ac.uk/download/pdf/553642413.pdf
[7] Law M and Collins A 2022 *Getting to Know ArcGIS Desktop 10.8* 6th ed (Esri Press)
[8] Thomson D L, Cooch E G and Conroy M J (eds) 2009 *Modeling Demographic Processes In Marked Populations* (*Environmental and Ecological Statistics* vol 3) (New York, NY: Springer) URL https://doi.org/10.1007/978-0-387-78151-8
[9] Gorlov P I, Siokhin V D, Polishchuk I K, Volokh A M and Gorlova A P 2022 *IOP Conference Series: Earth and Environmental Science* **1049**(1) 012069 URL https://doi.org/10.1088/1755-1315/1049/1/012069

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Temporal dynamics of steppe plant communities

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Abstract. Global climate change affects the conditions of ecosystems. However, the nature of changes induced by climatic factors remains unknown due to the complex nature of climatic transformations. The global trend of temperature increase is associated with an increase in precipitation and changes in its rhythm. The dynamics of plant communities under the influence of climate occurs against the background of natural successional phenomena. The aim of the study is to develop methodological approaches in order to identify aspects of vegetation variability that are caused by global climate change and give them an ecological interpretation. Geobotanical descriptions of vegetation in steppe ecosystems were carried out over the last 20 years. Exactly in this period dramatic climatic changes were observed, which allows to compare climatic and vegetation trends. For ecological interpretation the results of ordination of plant communities were explained with the help of phytoindication scales. Plant communities exhibit dynamics that are driven by endogenous and exogenous causes. These aspects of community dynamics were differentiated using the ordination procedure as different ordination axes. The axes that reflect endogenous dynamics were described using temporal variables. The axes that reflect exogenous dynamics were described using phytoindication scales. The phytoindication scales made it possible to assess the ecological directions of plant community transformation under the influence of global climate change. The transformation of the plant community under the influence of global climate change is inconsistent with the concepts of desertification. The revealed temporal patterns of the plant community have a complex and multidirectional trajectory. The plant community studied over the twenty-year investigation period exhibited a dynamic that is a superposition of two processes that are driven by the temperature and precipitation. The temperature trend is directional and reflects the tendency of global warming. This trend is accompanied by an increase in species richness and projective cover of the plant community. At the same time, thermophilicity and continentality of the community increase against the decrease of soil trophic status, acidity increase and soil carbonation decrease. Obviously, along with the mineralization of organic matter, the soil decarbonization can also be the cause of increased carbon dioxide emission into the atmosphere as a result of global warming. The trend, which is regulated by precipitation, is oscillatory. This trend changes the regime of moisture, light and cryoclimate of the plant community.

1. Introduction

The main feature of today's climate is increased global warming since the second half of the 1970s [1]. The global air temperature is predicted to increase steadily through the end of this century due to continued increases in greenhouse gases such as CO_2, and changes in land use such as deforestation of natural forests [2]. Due to global climate change, which affects the transformation of regional climate and the value of individual meteorological variables, the average monthly air temperature in Ukraine over the past decades differs from the values of the climatic norm. The air temperature has become higher for most months and for the year as a whole, only in September, November and December it decreased insignificantly [3]. The amount of atmospheric precipitation for the territory of Ukraine has not changed significantly, but the nature and intensity of precipitation has changed markedly [3]. The variability of precipitation dynamics affects the productivity of plant communities [4–6]. Recently, the number of cases where half or a month's worth of precipitation falls in a few hours has increased [3]. The forms of ecosystem transformation as a consequence of global climate change are accelerated desertification [7, 8]. The change of water regime in steppe ecosystems strongly affects ecosystem functioning, productivity and photosynthetic capacity [9–12]. The intensification and increased frequency of extreme climate change events, including high summer temperatures and increased precipitation variability, threaten sustainable development in semi-arid and arid regions through both biophysical and socioeconomic factors [13]. The stability of terrestrial ecosystems will be further threatened by the increasing frequency and severity of extreme climatic events [14, 15]. An increase in air temperature and uneven distribution of precipitation, which is stormy, localized in the warm season and does not provide an effective accumulation of moisture in the soil, can lead to an increase in the frequency and intensity of droughts. Changes in precipitation frequency, intensity, and pulse size, as well as seasonal changes in precipitation, affect arid ecosystem functions, including carbon flux [16–19], water exchange, and plant physiological status [20]. There are also changes in the values of extreme (maximum and minimum) temperatures. The minimum temperature has increased in almost all months and in the whole year. In the secular course of the maximum temperature in winter months, especially in January, there was a tendency to its growth. In summer months and for the year as a whole, the trend of maximum temperature change in the trend is insignificant, but in recent years, the maximum temperature increases. The particularly affected areas include grassland and desert ecosystems of semi-arid and arid areas [21–23]. A loss of biodiversity is an obvious consequence of climate change [22, 24]. The warming is evolving according to positive feedback dynamics. The combination of heat waves and variability in precipitation dynamics affect carbon exchange [25]. The global climate change is initiated by an increase in atmospheric concentrations of greenhouse gases, but the warming continuously stimulates the emission of carbon dioxide into the atmosphere [26–28]. An increase in air temperature leads to soil evaporation [8, 29–31]. The intensification of heat waves and abnormal precipitation led to the functional and structural degradation of particularly sensitive terrestrial ecosystems. The heat waves affect the intensity of plant growth [32–34]. Consequently, a water deficit occurs, further exacerbating ecological vulnerability and sensitivity and reducing resilience to rapid degradation in steppe regions [35,36]. An increase in precipitation in the steppe zone can improve the carbon balance, thereby mitigating the negative effects of a warming climate [37, 38]. The warming climate and increased precipitation variability can regulate the function and structure of ecosystems in steppe ecosystems. The transition from vegetation dominated by grasses to vegetation dominated by shrubs or tree species can be predicted [24]. The most important indicators of terrestrial ecosystem function are the primary production of aboveground plants and the activity of soil microorganisms [39]. The activity of soil microorganisms, which transform the biomass created by plants, determines the intensity of carbon sequestration and carbon dioxide emission into the atmosphere. The precipitation quantity affects the condition of the soil biota. Biomass, activity and composition of the microbial community are sensitive to the effects of environmental factors [40–42]. The water balance and temperature regime affect the functional state of soil biota [39, 43–45]. The biomass of soil biota decreases with warming [46–48], but increases with increased precipitation [49]. Estimating the balance of carbon, water, and energy in terrestrial ecosystems under conditions of climate change is possible only if the importance of microbial activity in ecosystem processes is elucidated [50].

2. Research aim and objectives

Grasslands provide many critical benefits to humans, including forage for livestock, food, biodiversity, carbon storage, and recreation [51]. Studies of the long-term dynamics of plant communities in steppe ecosystems are largely absent, and such studies are urgently needed to assess ecosystem responses and feedbacks to climate change [52].

The aim of the study is to develop methodological approaches in order to identify aspects of vegetation variability that are caused by global climate change and give them an ecological interpretation.

3. Material and methods

The Stone Graves reserve is located on the border between Donetsk and Zaporozhye regions, near the village of Nazarovka of Mariupol district on the Priazovsky upland, in the upper reaches of the Karatysh river, which is a tributary of the Berda river. The Stone Graves reserve has an area of about 400 hectares, of which almost 300 hectares are part of the Donetsk region and 100 hectares are part of the Zaporozhye region. The most part of the reserve area, about 200 hectares, falls on powerful granite rocky outcrops of Azov-Podolsky crystalline massif, towering above the surrounding steppe, which is the largest intrusive area in Donbass and Azov regions [53]. The rock outcrops are represented by the Western and Eastern ridges with absolute height of separate tops up to 100 m. According to landscape-geochemical zoning, the landscapes of the Stone Graves reserve are localized on eluvio-deluvium of crystalline rocks. According to the generic classification, these are loess uplands tending to erosion processes, so the migration of chemical elements here is weak and occurs when soils are washed away. The landscapes of the territory are characterised as self-purifying. The reserve is located in an area of elevated plains, where upward and downward radial migration of chemical elements takes place. The accumulation elements are Mn, Co, Sn, and the removal elements are Pb, Zn, Ni. Soil-forming rocks are clay and clayey sediments and loamy rubbly formations on eruptive and metamorphic rocks. The soils of the Stone Graves reserve are typical sparse humus black earths on loess-like loam and weathering products of crystalline rocks, which are the most productive along the bottom of the depression between two parallel ridges of rocks. Soil thickness decreases along the rock slopes along with disappearance of loess rocks and increase of area of weathering products of crystalline rocks to the day surface. The bottom of the basin between the ridges is dissected by gullies [54].

The stationary plot No.1 was created on July 14, 2000 to study the phenological development of steppe vegetation. The plot is located on the slope of 3° of eastern exposition along the upper edge of the amphitral catchment of the central gully of the inter-ridge trough at its headwaters. The geographic coordinates of the area center are N 47.310° E 37.076°. The elevation is 179 m above sea level. Vascular plant species lists were recorded for each 10 m × 10 m (the area is 100 m^2) sampling polygon along with a visual assessment of species coverage using a Braun-Blanquet scale [55]. The projective cover of plant species was measured at soil level. Plant taxonomic names follow the Euro+Med Plantbase resource (`https://europlusmed.org/`). Meteorological data obtained from NOAA climate data using the rnoaa package [56] for a language and environment for statistical computing R [57]. Based on the data obtained, indicators such as average spring temperature (figure 1, a), average temperature of the coldest month of the year (figure 1, b), and the amount of precipitation during the spring period of the year (figure 1, c) were calculated. The range scales values according to Y. Didukh [58] were used for phytoindication. Further, for phytoindication of environmental factors, we used the ideal indicator method of G. Buzuk [59]. Statistical calculations were carried out using the software Statistica 12.0 [60].

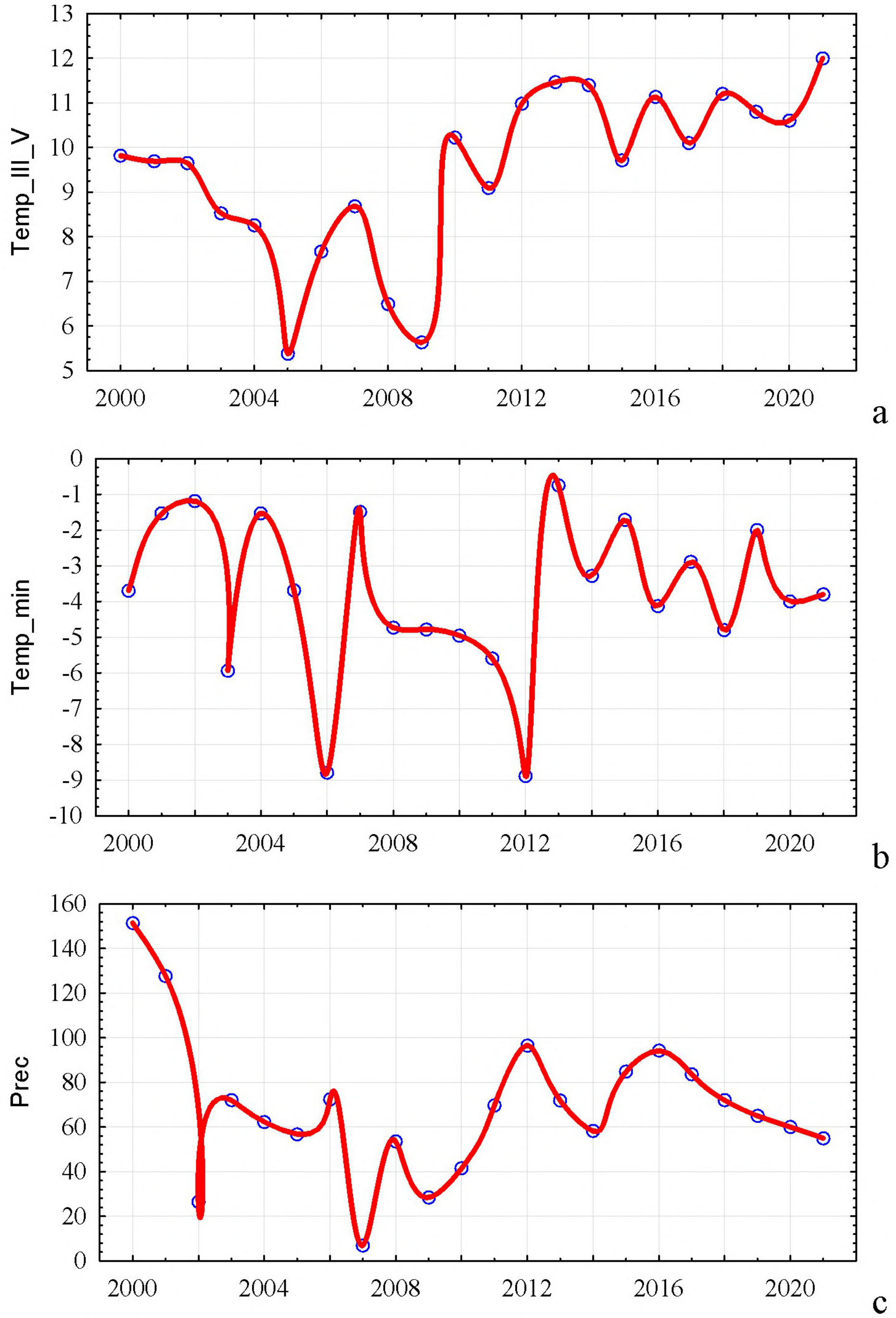

Figure 1: Dynamics of meteorological parameters during the study period 2000–2021: (a) average temperature during the spring period, °C (March-May); (b) the average temperature of the coldest month of the year, °C (January or February); (c) total spring precipitation (March–May), mm.

4. Results

The 79 plant species were found within the study area during the study period (table 1). The number of species in the community varied between 51 (in 2007) and 66 species (2014 and 2015). The number of species increased over time. There was a positive correlation ($r = 0.77$, $p < 0.001$)

between the number of species in the community and the order of years. The regression analysis revealed that the average rate of increase in the number of species in the community was 0.62 species per year. The projective cover of the community ranged from 70 to 85%. The projective cover showed an increasing trend. A statistically significant correlation ($r = 0.42$, $p = 0.05$) was found between the projective vegetation cover and the order of years. The projective cover increased on average by 0.4% with each year.

Table 1: Species diversity and abundance of the plant community (projective cover, %; + is signed that species presents).

Species	**Abundance**
Achillea nobilis L.	≤ 1
Achillea stepposa Klokov ex Krytzka	≤ 2
Adonis wolgensis Steven	≤ 2
Allium paczoskianum Tuzs.	≤ 2
Artemisia austriaca Jacq.	≤ 1
Asparagus officinalis subsp. *officinalis* L.	≤ 1
Bellevalia speciosa Woronow ex Grossh.	≤ 2
Berteroa incana (L.) DC.	+
Bromus riparius Rehmann	≤ 6
Campanula glomerata L.	+
Campanula sibirica L.	+
Carduus acanthoides L.	≤ 2
Carex caryophyllea Latourr.	≤ 2
Cirsium ukranicum Besser ex DC.	+
Consolida regalis subsp. *paniculate* (Host) Soó	≤ 1
Convolvulus arvensis L.	+
Cota tinctoria (L.) J. Gay	+
Elytrigia intermedia (Host) Nevski	≤ 10
Elytrigia intermedia subsp. *trichophora* (Link) Á. Löve D. Löve	≤ 40
Eryngium campestre L.	≤ 3
Erysimum diffusum Ehrh.	+
Euphorbia stepposa Zoz. ex Prokh.	≤ 3
Falcaria vulgaris Bernh	≤ 3
Festuca valesiaca Schleich. ex Gaudin	13-33
Galatella sedifolia subsp. *dracunculoides* (Lam.) Greuter	≤ 1
Galatella villosa (L.)	1-55
Galium octonarium (Klokov) Pobed.	≤ 2
Galium ruthenicum Willd.	+
Goniolimon tataricum (L.) Boiss.	≤ 1
Hesperis tristis L.	+
Hieracium virosum Pall.	+
Hypericum perforatum L.	+
Inula aspera Poir.	≤ 1
Inula oculus-christi L.	+
Jacobaea vulgaris Gaertn.	+
Klasea erucifolia (L.) Greuter ex Wagenitz	+
Koeleria cristata (L.) Pers.	≤ 2
Lavatera thuringiaca L.	≤ 2

Continued on next page

Table 1 – continued from previous page

Species	Abundanc
Limonium platyphyllum Lincz.	≤ 1
Linaria biebersteinii subsp. *maeotica* (Klokov) Ivanina	+
Linum austriacum L.	≤ 4
Medicago falcata L.	≤ 1
Melilotus officinalis (L.) Pall.	+
Odontites luteus (L.) Clairv.	+
Ornithogalum kochii Parl.	+
Phleum phleoides (L.) Karst.	≤ 2
Phlomis herba-venti subsp. *pungens* (Willd.) Maire ex DeFilipps	≤ 1
Phlomis tuberosa L.	≤ 1
Pilosella echioides (Lumn.) F.W. Schultz ex Sch. Bip.	+
Plantago lanceolata L.	+
Plantago media L.	≤ 1
Poa angustifolia L.	≤ 10
Potentilla humifusa Willd. ex Schltdl.	+
Potentilla recta subsp. *laciniosa* (Nestl.) Nyman	+
Prunus spinosa subsp. *dasyphylla* (Schur) Domin	≤ 3
Ranunculus scythicus Klokov ex Grossh.	≤ 1
Rhinanthus angustifolius subsp. *grandifloras* (Wallr.) D. A. Webb	+
Rosa corymbifera Borkh.	≤ 1
Salvia nemorosa subsp. *tesquicola* (Klokov ex Pobed.) Soó	≤ 3
Salvia nutans L.	≤ 5
Scabiosa ochroleuca L.	+
Scorzonera molis M. Bieb.	+
Securigera varia (L.) Lassen)	≤ 5
Seseli campestre Besser	+
Silene bupleuroides L.	+
Silene wolgensis (Hornem.) Otth	+
Stachys recta L.	≤ 1
Stipa capillata L.	≤ 5
Stipa pulcherrima K. Koch	≤ 2
Taraxacum officinale Webb. ex Wigg.	+
Taraxacum serotinum (Waldst ex Kit) Roir	≤ 2
Teucrium polium L.	≤ 2
Thalictrum minus L.	≤ 1
Thesium arvense Horvalovszky	+
Thymus pulegioides subsp. *pannonicus* (All.) Kerguélen	≤ 5
Turritis glabra L.	≤ 1
Verbascum densiflorum Bertol.	+
Veronica austriaca L.	+
Veronica verna L.	+

The phytoindication score of soil water regime ranged from 3.69 to 3.98 (table 2), corresponding to plant available moisture of 32–33% (figure 2). This indicator did not show a stable linear trend of variability over time, as indicated by the lack of statistically significant correlation with the order of years (r = –0.04, p = 0.85). It depended on spring precipitation (r = 0.64, p = 0.001) and on precipitation in the preceding year, which can be described by regression equation: Hd = 32.0+0.00754 $Prec_{spr}$ + 0.00178 –$Prec_{prev}$ ($R^2_{adj} = 0.47$, $p < 0.001$), where $Prec_{spr}$ is the total spring precipitation in current year; $Prec_{prev}$ is the total precipitation in preceding year. The amount of precipitation that the region receives on average is sufficient to accumulate significant water reserves, if the soil properties allow it. The soils on which the community under study has formed have a very low water-holding capacity, so the plant species that make up the community are highly xerophilous.

Table 2: Descriptive statistics of phytoindicator estimates of environmental factors.

Ecological factor	Mean±st.error	Minimum	Maximum	CV, %
Soil water regime (Hd)	3.81±0.019	3.69	3.98	2.30
Variability of damping (fH)	5.93±0.043	5.47	6.24	3.38
Soil acidity (Rc)	9.75±0.067	9.18	10.49	3.25
Total salt regime (Sl)	7.45±0.079	6.80	8.34	4.98
Carbonate content in soil (Ca)	11.46±0.033	11.22	11.73	1.36
Nitrogen content in soil (Nt)	3.22±0.086	2.68	3.98	12.54
Soil aeration (Ae)	5.40±0.041	4.96	5.71	3.53
Thermal climate (Tm)	10.24±0.087	9.63	11.29	4.00
Humidity or ombroclimate (Om)	9.94±0.075	9.25	10.46	3.52
Continentality of climate (Kn)	12.38±0.073	11.87	13.15	2.78
Cryo-regime (Cr)	8.87±0.068	8.30	9.52	3.62
Light regime (Lc)	8.91±0.007	8.87	8.96	0.39

The moisture contrast regime was characterized by indices that were in the range of 5.47–6.24. The moisture contrast regime exhibited a steady linear trend of decreasing indices over time, as indicated by a negative statistically significant correlation with the order of years (r = –0.49, p = 0.02). The soil acidity was characterized by phytoindicator scores that ranged from 9.18–10.49, which corresponded to a soil acidity pH of 6.8–7.2. The acidity decreased linearly with time (r = –0.69, $p < 0.001$). It should also be noted that acidity was negatively correlated with mean spring temperature (r = –0.47, p = 0.027). The overall salinity regime was characterized by phytoindication scores, which were in the range of 6.8–8.34, which corresponded to a salt content of 0.031–0.060% in the soil solution. The overall salinity regime showed an increasing trend with time (r = 0.68, p = 0.001) and was also positively correlated with mean spring temperature (r = 0.62, p = 0.001). The content of carbonate in soil was characterized by phytoindicator indices, which were in the range 11.22–11.73, which corresponded to the content of carbonate in soil 8.6–11.3%. The carbonate content in soil showed a decreasing trend with time (r = –0.71, p = 0.001), and was also negatively correlated with mean spring temperature (r = –0.62, p = 0.001). The soil nitrogen content was characterized by phytoindicator indices, which were in the range 2.68–3.98, which corresponded to the content of plant-available nitrogen in the soil of 0.044–0.11%. The soil nitrogen content showed a decreasing trend with time (r = –0.87, p = 0.001), and also negatively correlated with mean spring temperature (r = –0.74, p = 0.001). The soil aeration regime was characterised by phytoindication indices, which were in the range 4.96–5.71, corresponding to an aeration porosity of 65–77%. This index was stationary over time.

The thermal climate was characterised by phytoindicator indices that ranged from 9.63–11.29, which corresponded to a radiative balance of 2016–2250 MJ m^{-2} year^{-1}. The radiation balance estimate showed an increasing trend with time (r = 0.66, p = 0.001) and was also positively correlated with mean spring temperature ($r = 0.65$, $p = 0.001$). The ombroclimate was characterised by phytoindicator indices that ranged from 9.25–10.46, corresponding to a difference between precipitation and evaporation of –722 – –485 mm. The ombroclimate assessment was positively correlated with the average temperature of the coldest month ($r = 0.41$, $p = 0.05$). The continentality was characterised by phytoindication indices, which were in the range 11.87–13.15, corresponding to a continentality index of 159–172%. The continentality score showed an increasing trend with time ($r = 0.75$, $p = 0.001$). The phytoindication of the cryo-climate score corresponds to the average temperature of the coldest month –6 – –3°C and correlates positively with these meteorological indices measured instrumentally ($r = 0.51$, $p = 0.016$). Lighting regime was characterised by scores of 8.87–8.96. The lighting regime was stationary during the study period.

The principal component analysis identified two components, which together describe 53.1% of the variation in the original variables (figure 3). The principal component 1 describes a trend of increasing number of species in the community, thermal regime, soil salinity and continentality over time and decreasing indicators of plant nitrogen nutrition, carbonation and acidity. The principal component 2 reflects a positive effect of precipitation and temperature in the coldest month of the year on moistening, ombrorheme and cryoregime and a negative effect on aeration and lighting regimes.

5. Discussion

In dynamic ecosystems, such as steppes, environmental fluctuations determine community composition [61, 62]. Grasslands are also affected by ongoing climate change [63–65]. Anthropogenic impacts result in significant changes in environmental factors that affect the composition and functioning of plant communities [66]. Identifying the causes that drive changes in the structure of plant communities is critical because the composition of plant communities affects important ecosystem functions and services [67,68]. Fluctuations are short-term changes in the structure of plant communities on the scale of several years [69, 70]. In contrast to succession, these changes are characterized by the absence of long-term trends in the structure of communities in one direction or another, the possibility of returning to a state close to the initial one, and the absence of significant changes in the floristic composition. Most often fluctuations are considered as changes occurring within one solar cycle (about 11 years) [71]. Fluctuations can be caused by various factors. The fluctuations can be ecotypic, anthropic, zoogenic, phytocyclic, phytoparasitic [72]. The ecotopic fluctuations are caused by variability in meteorological and hydrological conditions [73, 74]. Ecotope changes can cause a chain of different mechanisms of impact on vegetation cover. Drought is associated with higher temperatures and increased salinity in arid regions [75–77], and can also cause mass development of locusts that consume a significant portion of organic matter [78]. Drought has the greatest impact on plant communities developing on sparse soils [79–81].

The potential to interpret and predict the response of plant communities to global change is complicated by many factors, such as the type of driver of global change and the ecological context [82–84]. The phytoindication of the moisture content indicates that conditions within the study area are favourable for peroxerophytes and xerophytes. These conditions are characteristic of steppe herbaceous communities on rocky ground. In conditions of precipitation deficit on stony soils petrophytic communities are formed which specificity consists in high level of species and syntaxonomy endemism [53]. The precipitation levels observed in the study area can allow for the formation of significantly larger water reserves. However, the unfavourable water-physical properties of soils formed on rocks do not allow for the accumulation of water in larger quantities. As a result, the plant community is formed by species that are able to tolerate water deficits. The phytoindication assessment of moisture depends on the precipitation conditions of the current and previous year. The ecological structure of the plant community also changes according

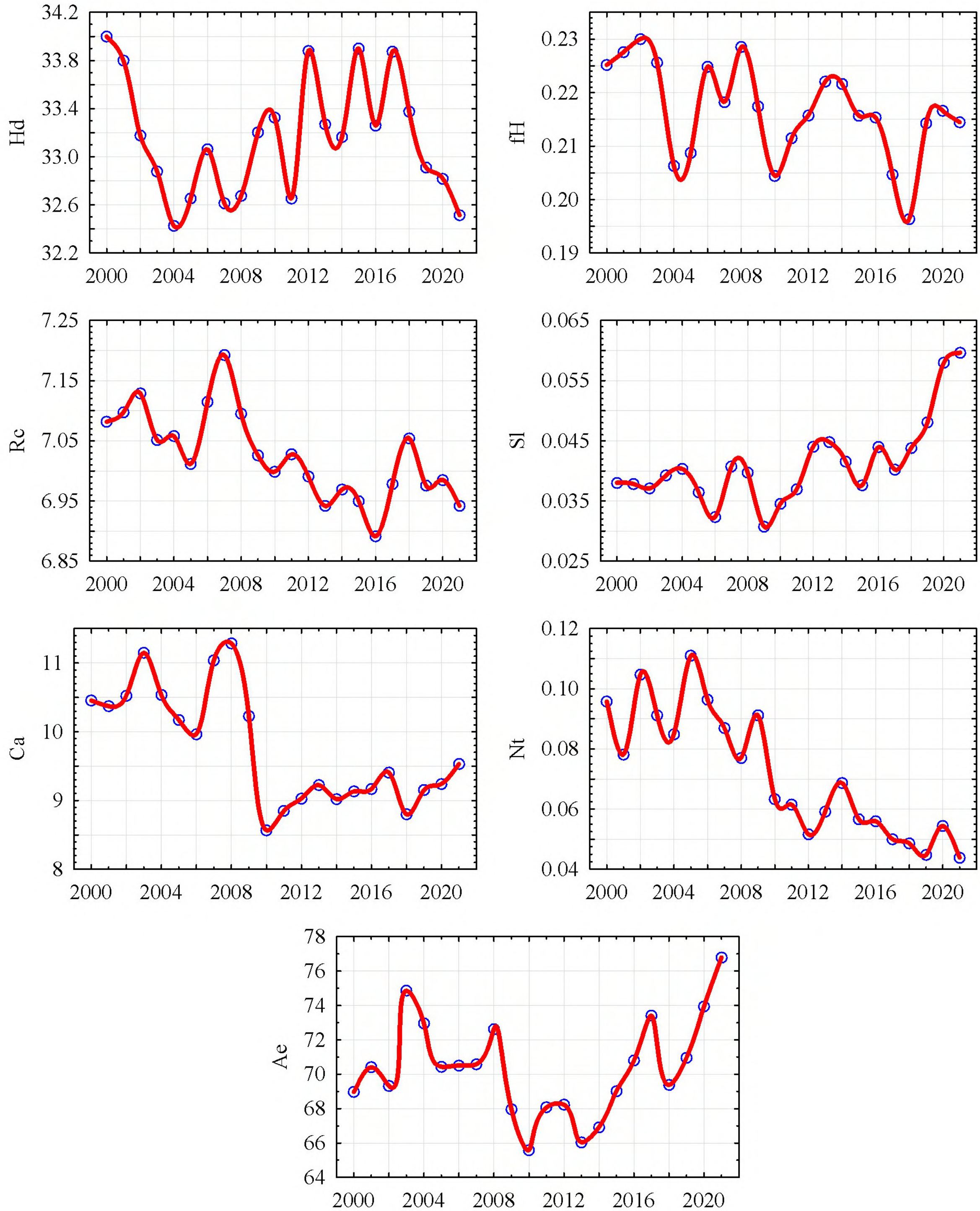

Figure 2: Dynamics of soil environmental factors assessed by phytoindication: Hd is the plant available soil water content, %; fH is the index of variability of damping, which varies from 0 to 0.5; Rc is the soil acidity (pH); Sl is the salt content in the soil solution (mg/l); Ca is the carbonate content in soil (%); Nt is the content in soil plant accessible forms of nitrogen (%); Ae is the aeration porosity (%).

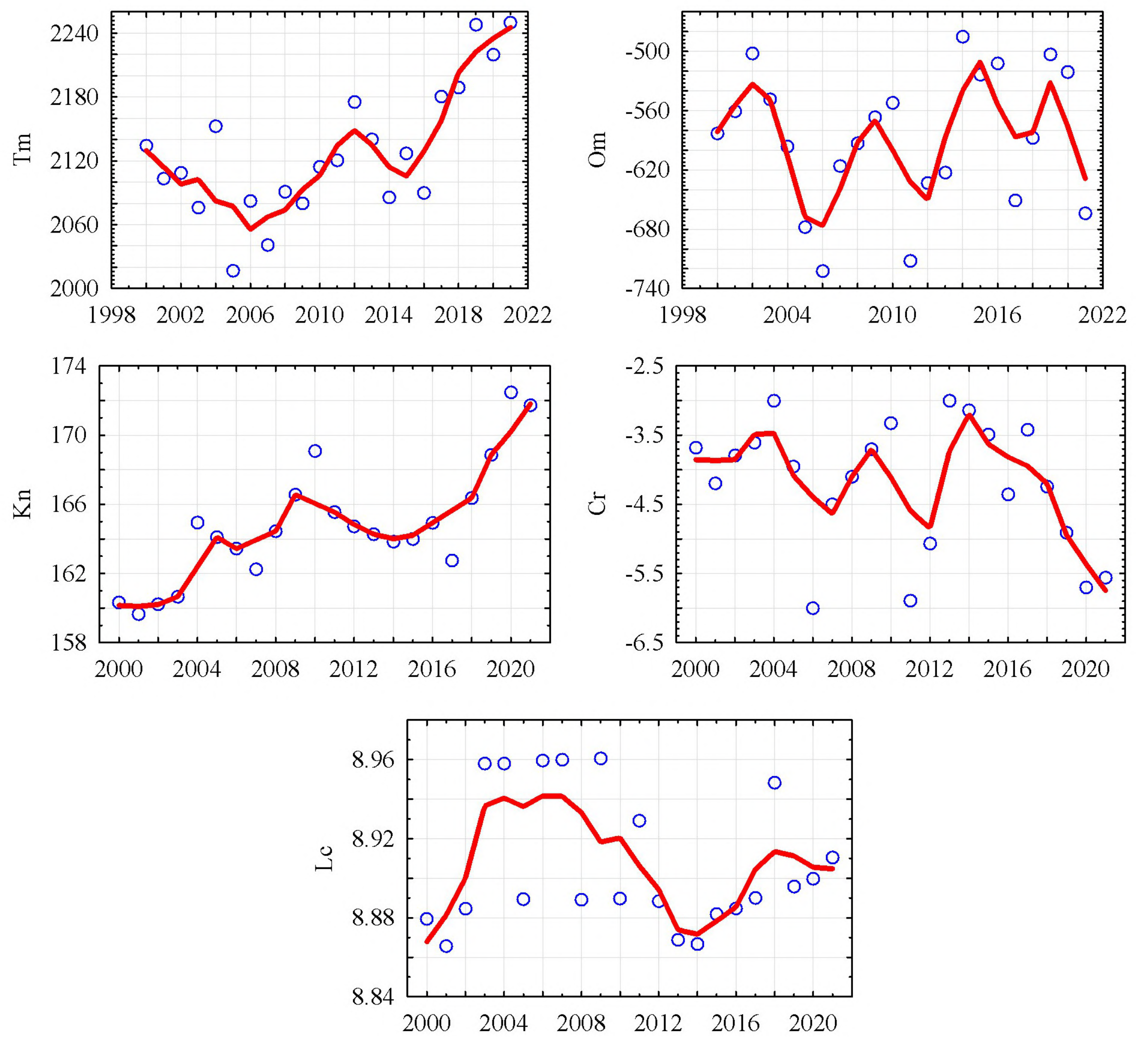

Figure 3: Dynamics of climatic factors assessed by phytoindication: Tm is the radiation balance (m^{-2} $year^{-1}$); Om is the humidity index determined as a difference between annual precipitation quantity and evaporation (mm); Kn is the index of continentality (%); Cr is the mean temperature of the coldest month of the year (C); Lc is the light regime in 9-grade scale.

to precipitation trends. These changes have a fluctuational character, as they do not show a stable directional trend. The level of soil moisture is naturally inversely correlated with soil aeration conditions. Accordingly, the level of soil aeration does not show a directional trend. Rainfall levels in the spring are coordinated with the temperature of the coldest month of the year. The warmer the winter in a given year, the better the soil moisture conditions will be. This relationship is the reason for the correlation of phytoindication estimates of moisture, ombroclimate and cryoclimate. This relationship is the reason for the correlation between the phytoindication estimates of cryoclimate and instrumental temperature measurements. Higher temperatures in winter months and higher precipitation contribute to lower light levels in the plant community. Obviously, these factors contribute to an increase in the phytomass of the plant community and thus a decrease in its illumination. Once again, the variation in precipitation and temperature during winter time did not show a directional temporal trend. These variables are described by variation in principal component 2, which is characterised by autocorrelation with

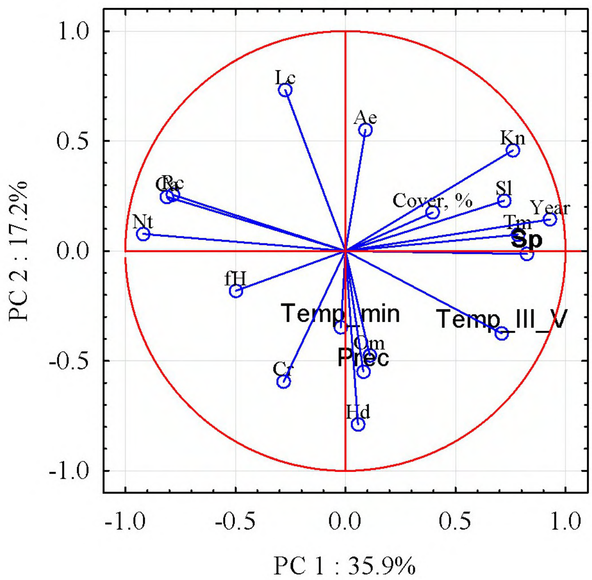

Figure 4: Principal component analysis of variation in phytoindicator estimates of environmental factors, species richness, projective cover of the plant community, average temperature of the coldest month of the year, average temperature and amount of precipitation in spring.

lags of 1, 13 and 14 years (positive autocorrelation) and 6–7 years (negative autocorrelation). The presence of an oscillatory process is fully consistent with the notion of plant community dynamics as a fluctuation. The species composition of plants in a dry grassland in Central Europe showed marked dynamics from year to year in response to weather conditions in the previous two years. These changes in the community are undirected and have contributed to the stability of this community, which has not changed significantly over the past 90 years. However, increased drought frequency due to ongoing climate change may lead to directional changes with the expansion of ruderal species [69].

Environmental changes and resource availability are key mechanisms that support biodiversity [85–87]. Weather fluctuations prevent competitive exclusion between species co-occurring at a site and, at the same time, allow species with different strategies and from different climatic regions to co-exist at the edge of their ecological niches [61]. Differences in response to climatic extremes between species with different ecological strategies can lead to non-equilibrium coexistence due to stochastic fluctuations between years [88]. When weather conditions are favourable for a certain type of species strategy, other species may be reduced and confined to small areas partly because of direct response to the environment and partly because of competition. As soon as the weather shifts to a state favourable to other types of strategies, species with those strategies spread out again, compensating for their losses in the previous period of time [85]. This is particularly true for dry grasslands on shallow, stony soils with low water retention, which are characterised by considerable species turnover in response to weather fluctuations, but remain stable in the long term [89].

Other ecological factors and species richness of the community show a consistent directional trend of change over time. Climate change is considered a leading threat to biodiversity because it may increase the rate of species extinction. In addition to extinctions, the distribution of species is predicted to shift as a result of variations in temperature and precipitation around the world [90]. Climate change is also expected to increase weather fluctuations within and between successive years. Extreme climate events and increased seasonal variations have already been reported around the world [91]. This trend is driven by directional changes in temperature regime and is described by principal component 1. After extracting the linear trend, principal component 1 did not exhibit an oscillatory component. Over the study period, the species richness of the community and projective cover increased together with the thermoclimate, continentality and salinity of the soil solution. Also such indicators as the level of nitrogen compounds supply to plants, acidity, moisture regime variability and soil carbonate content decreased throughout the study period. Variations in the availability of resources, such as atmospheric carbon dioxide, nitrogen, and precipitation patterns, can have significant consequences for the structure of plant communities [92].

Biotic processes, such as shifts in competitive dominance or susceptibility to herbivory, and abiotic factors, such as environmental filtration, affect the richness and composition of plant communities at local scales [93–95]. The conditions of soil moisture variability are favourable for hemicontrastophobes, which are characteristic of ecotopes with moderately uneven moistening of the root-containing soil layer, which is completely soaked by precipitation only in some rainy seasons. The steppe zone of Ukraine is generally characterised by uneven precipitation and rainfall that is of a torrential nature. Such meteorological features lead to an extremely uneven soil moisture regime against a background of water scarcity.

Community composition and change in richness varies from place to place depending on the environment, as well as fluctuations in weather conditions, combined with inherent population and community dynamics over time [96]. Such dynamics can best be understood with detailed long-term observations at stationary plots [69,97,98]. The phytoindication method estimates soil acidity as being in the pH range of 6.8–7.2. This agrees with the results obtained experimentally. The acidity of soils in the reserve is pH7.0 and ranges from pH5.9 to 7.6 [54]. This result confirms the high accuracy of phytoindication assessments of environmental factors, which can be achieved by studying multi-species plant communities. It is legitimate that the decrease in soil acidity was accompanied by a decrease in soil carbonate content. It should be noted that carbonates are an important carbon reserve in the soil. The decrease of carbonate content in the soil due to global warming is an important source of its supply to the atmosphere. It is obvious that decarbonisation of soil is accompanied by transition of insoluble calcium and magnesium salts into soluble forms that is accompanied by increase in indicators of mineralisation of a soil solution. The mineralisation of the soil solution is not significant, so this factor cannot act as a limiting factor. Increased environmental stress can have various effects on plant community composition, either shifting or increasing niche availability. The repeated removal of plant material by haying can increase species richness by increasing light availability and creating favorable conditions for species that can tolerate aboveground removal. Increased drought or temperature stress can reduce the species richness of plants because many species will not be able to persist under these new conditions [99, 100].

Empirical data and theoretical evidence suggest that the response of ecosystem functions attenuates as the number of simultaneously introduced factors increases due to the leveling out of positive and negative effects on functions such as productivity and nutrient cycling [101,102]. Adding resources (e.g., nutrients) is predicted to reduce plant species richness and change plant community composition due to alterations in competitive interactions between species for remaining limiting resources (e.g., water or light) [103, 104]. The nitrate content of the reserve's soils is 179 µg/g and varies between 93 and 348 µg/g [54]. A decrease in the supply of soil nutrients, mainly nitrogen compounds, may be a factor in stimulating an increase in the species diversity of the community. Obviously, an increase in temperature leads to an equilibrium shift in the processes of mineralisation and humification of organic matter in the soil towards mineralisation, which leads to a decrease in nutrient reserves. In turn, this transformation initiates a decrease in soil acidity and decarbonization as a consequence of increased soil respiration and destruction of soil carbonates. The combined effect of multiple transforming factors causes a stronger effect on the plant community [105, 106].

6. Conclusion

The plant community studied over the twenty-year investigation period exhibited a dynamic that is a superposition of two processes that are driven by the temperature and precipitation. The temperature trend is directional and reflects the tendency of global warming. This trend is accompanied by an increase in species richness and projective cover of the plant community. At the same time, thermophilicity and continentality of the community increase against the decrease of soil trophic status, acidity increase and soil carbonation decrease. Obviously, along with the mineralization of organic matter, the soil decarbonization can also be the cause of increased carbon dioxide emission into the atmosphere as a result of global warming. The trend, which is regulated by precipitation, is oscillatory. This trend changes the regime of moisture, light and cryoclimate of the plant community.

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References

[1] Zolotokrylin A N 2019 *Izvestiya Rossiiskoi akademii nauk. Seriya geograficheskaya* 3–13
[2] Cramer W, Bondeau A, Woodward F I, Prentice I C, Betts R A, Brovkin V, Cox P M, Fisher V, Foley J A, Friend A D, Kucharik C, Lomas M R, Ramankutty N, Sitch S, Smith B, White A and Young-Molling C 2001 *Global Change Biology* **7** 357–373
[3] Balabukh V O 2013 Changes in the intensity of convection in ukraine: causes and consequences
[4] Fang J, Piao S, Zhou L, He J, Wei F, Myneni R B, Tucker C J and Tan K 2005 *Geophysical Research Letters* **32** L21411
[5] Knapp A K, Fay P A, Blair J M, Collins S L, Smith M D, Carlisle J D, Harper C W, Danner B T, Lett M S and McCarron J K 2002 *Science* **298** 2202–2205
[6] Thomey M L, Collins S L, Vargas R, Johnson J E, Brown R F, Natvig D O and Friggens M T 2011 *Global Change Biology* **17** 1505–1515
[7] Grimm N B, Chapin F S, Bierwagen B, Gonzalez P, Groffman P M, Luo Y, Melton F, Nadelhoffer K, Pairis A, Raymond P A, Schimel J and Williamson C E 2013 *Frontiers in Ecology and the Environment* **11** 474–482
[8] Reynolds J F, Smith D M S, Lambin E F, Turner B L, Mortimore M, Batterbury S P J, Downing T E, Dowlatabadi H, Fernández R J, Herrick J E, Huber-Sannwald E, Jiang H, Leemans R, Lynam T, Maestre F T, Ayarza M and Walker B 2007 *Science* **316** 847–851
[9] Knapp A K, Beier C, Briske D D, Classen A T, Luo Y, Reichstein M, Smith M D, Smith S D, Bell J E, Fay P A, Heisler J L, Leavitt S W, Sherry R, Smith B and Weng E 2008 *BioScience* **58** 811–821
[10] Reynolds J F, Kemp P R, Ogle K and Fernández R J 2004 *Oecologia* **141** 194–210
[11] Wilcox K R, Fischer J C, Muscha J M, Petersen M K and Knapp A K 2015 *Global Change Biology* **21** 335–344
[12] Xu Z, Zhou G and Shimizu H 2009 *Journal of Experimental Botany* **60** 3737–3749
[13] Schröter D, Cramer W, Leemans R, Prentice I C, Araújo M B, Arnell N W, Bondeau A, Bugmann H, Carter T R, Gracia C A, de la Vega-Leinert A C, Erhard M, Ewert F, Glendining M, House J I, Kankaanpää S, Klein R J T, Lavorel S, Lindner M, Metzger M J, Meyer J, Mitchell T D, Reginster I, Rounsevell M, Sabaté S, Sitch S, Smith B, Smith J, Smith P, Sykes M T, Thonicke K, Thuiller W, Tuck G, Zaehle S and Zierl B 2005 *Science* **310** 1333–1337
[14] Diffenbaugh N S and Field C B 2013 *Science* **341** 486–492
[15] Ponce-Campos G E, Moran M S, Huete A, Zhang Y, Bresloff C, Huxman T E, Eamus D, Bosch D D, Buda A R, Gunter S A, Scalley T H, Kitchen S G, McClaran M P, McNab W H, Montoya D S, Morgan J A, Peters D P C, Sadler E J, Seyfried M S and Starks P J 2013 *Nature* **494** 349–352
[16] Huxman T E, Cable J M, Ignace D D, Eilts J A, English N B, Weltzin J and Williams D G 2004 *Oecologia* **141** 295–305
[17] Liu R, Cieraad E, Li Y and Ma J 2016 *Ecosystems* **19** 601–614
[18] Potts D L, Huxman T E, Cable J M, English N B, Ignace D D, Eilts J A, Mason M J, Weltzin J F and Williams D G 2006 *New Phytologist* **170** 849–860

[19] Shen W, Jenerette G D, Hui D and Scott R L 2016 *Biogeosciences* **13** 425–439
[20] Aragón C F, Escudero A and Valladares F 2007 *Journal of Ecology* **96** 222–229
[21] Ignace D and Huxman T 2009 *Journal of Arid Environments* **73** 626–633
[22] Morgan J A, LeCain D R, Pendall E, Blumenthal D M, Kimball B A, Carrillo Y, Williams D G, Heisler-White J, Dijkstra F A and West M 2011 *Nature* **476** 202–205
[23] Volder A, Briske D D and Tjoelker M G 2013 *Global Change Biology* **19** 843–857
[24] Volder A, Briske D and Tjoelker M 2013 *Global Change Biology* **19**
[25] Carlyle C N, Fraser L H and Turkington R 2014 *Oecologia* **174** 1065–1073
[26] De Boeck H J, Lemmens C M H M, Vicca S, Van den Berge J, Van Dongen S, Janssens I A, Ceulemans R and Nijs I 2007 *New Phytologist* **175** 512–522
[27] Huxman T E, Snyder K A, Tissue D, Leffler A J, Ogle K, Pockman W T, Sandquist D R, Potts D L and Schwinning S 2004 *Oecologia* **141** 254–268
[28] Sokolov S G and Zhukov A V 2014 *Biology Bulletin* **41** 468–477
[29] Dai A 2013 *Nature Climate Change* **3** 52–58
[30] Maestre F T, Salguero-Gómez R and Quero J L 2012 *Philosophical Transactions of the Royal Society B: Biological Sciences* **367** 3062–3075
[31] Reynolds J F, Stafford Smith D M, Lambin E F, Turner B L, Mortimore M, Batterbury S P, Downing T E, Dowlatabadi H, Fernández R J, Herrick J E, Huber-Sannwald E, Jiang H, Leemans R, Lynam T, Maestre F T, Ayarza M and Walker B 2007 *Science* **316** 847–851
[32] Ciais P, Reichstein M, Viovy N, Granier A, Ogée J, Allard V, Aubinet M, Buchmann N, Bernhofer C, Carrara A, Chevallier F, De Noblet N, Friend A D, Friedlingstein P, Grünwald T, Heinesch B, Keronen P, Knohl A, Krinner G, Loustau D, Manca G, Matteucci G, Miglietta F, Ourcival J M, Papale D, Pilegaard K, Rambal S, Seufert G, Soussana J F, Sanz M J, Schulze E D, Vesala T and Valentini R 2005 *Nature* **437** 529–533
[33] Rustad L, Campbell J, Marion G, Norby R, Mitchell M, Hartley A, Cornelissen J and Gurevitch J 2001 *Oecologia* **126** 543–562
[34] Wan S, Xia J, Liu W and Niu S 2009 *Ecology* **90** 2700–2710
[35] De Boeck H J, Bassin S, Verlinden M, Zeiter M and Hiltbrunner E 2016 *New Phytologist* **209** 531–541
[36] Liu T, Xu Z Z, Hou Y H and Zhou G S 2016 *Plant and Soil* **400** 15–27
[37] Hutchison J S and Henry H A L 2010 *Ecosystems* **13** 661–672
[38] Niu S, Wu M, Han Y, Xia J, Li L and Wan S 2008 *New Phytologist* **177** 209–219
[39] Schimel J, Balser T C and Wallenstein M 2007 *Ecology* **88** 1386–1394
[40] Cable J M and Huxman T E 2004 *Oecologia* **141** 317–324
[41] Liu W, Zhang Z and Wan S 2009 *Global Change Biology* **15** 184–195
[42] Nielsen U N and Ball B A 2015 *Global Change Biology* **21** 1407–1421
[43] Luo Y, Wan S, Hui D and Wallace L L 2001 *Nature* **413** 622–625
[44] Melillo J M, Steudler P A, Aber J D, Newkirk K, Lux H, Bowles F P, Catricala C, Magill A, Ahrens T and Morrisseau S 2002 *Science* **298** 2173–2176
[45] Sheik C S, Beasley W H, Elshahed M S, Zhou X, Luo Y and Krumholz L R 2011 *The ISME Journal* **5** 1692–1700
[46] Alasmary Z, Todd T, Hettiarachchi G M, Stefanovska T, Pidlisnyuk V, Roozeboom K, Erickson L, Davis L and Zhukov O 2020 *Agronomy* **10** 1727
[47] Rinnan R, Michelsen A, Bååth E and Jonasson S 2007 *Global Change Biology* **13** 28–39
[48] Zhang W, Parker K M, Luo Y, Wan S, Wallace L L and Hu S 2005 *Global Change Biology* **11** 266–277
[49] Sanaullah M, Blagodatskaya E, Chabbi A, Rumpel C and Kuzyakov Y 2011 *Applied Soil Ecology* **48** 38–44
[50] Allison S D, Wallenstein M D and Bradford M A 2010 *Nature Geoscience* **3** 336–340
[51] Xu Z, Hou Y, Zhang L, Liu T and Zhou G 2016 *Scientific Reports* **6** 34801
[52] Bardgett R D, Manning P, Morriën E and De Vries F T 2013 *Journal of Ecology* **101** 334–343
[53] Didukh Y, Borsukevych L, Davydova A, Dziuba T, Dubyna D, Iemelianova S, Kuzemko A, Kolomiychuk V, Kucher O, Khodosovtsev O, Pashkevych N, Moysiyenko I, Fitsailo T, Tsarenko P, Chusova O, Shapoval V and Shyriaeva D 2020 *Biotopes of Steppe zone of Ukraine* (Chernivtsi: DrukArt)
[54] Yazvinskaya M and Zhuk A 2009 *Investigative and Ecological Geochemistry* **1** 56–68
[55] Westhoff V and Van Der Maarel E 1978 *The Braun-Blanquet Approach* (Springer Netherlands) p 287–399
[56] Chamberlain S 2020
[57] Team R C 2020 *R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.* **2** https://www.R–project.org
[58] Didukh Y P 2011 *The ecological scales for the species of Ukrainian flora and their use in synphytoindication* (Phytosociocenter)
[59] Buzuk G N 2017 *Bulletin of Pharmacy* **2** 31–37

[60] 2014 (13)
[61] Adler P B, HilleRisLambers J, Kyriakidis P C, Guan Q and Levine J M 2006 *Proceedings of the National Academy of Sciences* **103** 12793–12798
[62] Ponomarenko O, Banik M and Zhukov O 2021 *Ekológia (Bratislava)* **40** 154–162
[63] Erdős L, Ambarlı D, Anenkhonov O A, Bátori Z, Cserhalmi D, Kiss M, Kröel-Dulay G, Liu H, Magnes M, Molnár Z, Naqinezhad A, Semenishchenkov Y A, Tölgyesi C and Török P 2018 *Applied Vegetation Science* **21** 345–362
[64] Woodward F I and Lomas M R 2004 *Biological Reviews* **79** 643–670
[65] Zhukov O, Yorkina N, Budakova V and Kunakh O 2021 *International Journal of Environmental Studies* 1–17
[66] Stefanovska T, Skwiercz A, Zouhar M, Pidlisnyuk V and Zhukov O 2021 *International Journal of Environmental Science and Technology* **18** 57–72
[67] Cardinale B J, Matulich K L, Hooper D U, Byrnes J E, Duffy E, Gamfeldt L, Balvanera P, O'Connor M I and Gonzalez A 2011 *American Journal of Botany* **98** 572–592
[68] Smith M D, Knapp A K and Collins S L 2009 *Ecology* **90** 3279–3289
[69] Fischer F M, Chytrý K, Těšitel J, Danihelka J and Chytrý M 2020 *Journal of Vegetation Science* **31** 711–721
[70] Koshelev O, Koshelev V, Fedushko M and Zhukov O 2021 *Folia Oecologica* **48** 118–135
[71] Onipchenko V 2013 *Functional phytocenology. Plant synecology* (Krasand)
[72] Rabotnov T 1983 *Phytocenology: Textbook for universities in specialty "Biology"* 2nd ed (Publishing house of Moscow State University)
[73] Budakova V S, Yorkina N V, Telyuk P M, Umerova A K, Kunakh O M and Zhukov O V 2021 *Biosystems Diversity* **29** 78–87
[74] Kubiak-Wójcicka K 2020 *Resources* **9** 103
[75] Bondarev D, Fedushko M, Hubanova N, Novitskiy R, Kunakh O and Zhukov O 2022 *Ichthyological Research*
[76] Hassani A, Azapagic A and Shokri N 2021 *Nature Communications* **12** 6663
[77] Hussain S, Shaukat M, Ashraf M, Zhu C, Jin Q and Zhang J 2019 *Salinity Stress in Arid and Semi-Arid Climates: Effects and Management in Field Crops* (IntechOpen)
[78] Peng W, Ma N L, Zhang D, Zhou Q, Yue X, Khoo S C, Yang H, Guan R, Chen H, Zhang X, Wang Y, Wei Z, Suo C, Peng Y, Yang Y, Lam S S and Sonne C 2020 *Environmental Research* **191** 110046
[79] Bloor J M and Bardgett R D 2012 *Perspectives in Plant Ecology, Evolution and Systematics* **14** 193–204
[80] Sardans J and Peñuelas J 2013 *Plant and Soil* **365** 1–33
[81] Shcherbyna V V, Maltseva I A, Maltseva H V and Zhukov O V 2021 *Biosystems Diversity* **29** 3–9
[82] Chalcraft D R, Cox S B, Clark C, Cleland E E, Suding K N, Weiher E and Pennington D 2008 *Ecology* **89** 2165–2171
[83] Domnich V I, Domnich A V and Zhukov O V 2021 *Biosystems Diversity* **29** 195–206
[84] Elahi R, O'Connor M I, Byrnes J E, Dunic J, Eriksson B K, Hensel M J and Kearns P J 2015 *Current Biology* **25** 1938–1943
[85] Chesson P L and Warner R R 1981 *The American Naturalist* **117** 923–943
[86] Descamps-Julien B and Gonzalez A 2005 *Ecology* **86** 2815–2824
[87] Tredennick A T, Adler P B and Adler F R 2017 *Ecology Letters* **20** 958–968
[88] Wilson J B 2011 *Journal of Vegetation Science* **22** 184–195
[89] Dostálek J and Frantík T 2011 *Biologia* **66** 837– 847
[90] Porfirio L L, Harris R M B, Lefroy E C, Hugh S, Gould S F, Lee G, Bindoff N L and Mackey B 2014 *PLoS ONE* **9** e113749
[91] Spinoni J, Vogt J V, Naumann G, Barbosa P and Dosio A 2018 *International Journal of Climatology* **38** 1718–1736
[92] Franklin J, Serra-Diaz J M, Syphard A D and Regan H M 2016 *Proceedings of the National Academy of Sciences* **113** 3725–3734
[93] Chesson P 2000 *Annual Review of Ecology and Systematics* **31** 343–366
[94] Grime J P 1973 *Nature* **242** 344–347
[95] HilleRisLambers J, Adler P B, Harpole W S, Levine J M and Mayfield M M 2012 *Annual Review of Ecology, Evolution, and Systematics* **43** 227–248
[96] Herben T, Krahulec F, Hadincová V and Skálová H 1993 *Journal of Vegetation Science* **4** 163–170
[97] Dunnett N P, Willis A J, Hunt R and Grime J P 1998 *Journal of Ecology* **86** 610–623
[98] Watkinson A and Ormerod S 2001 *Journal of Applied Ecology* **38** 233–237
[99] Deru J G, Bloem J, de Goede R, Keidel H, Kloen H, Rutgers M, van den Akker J, Brussaard L and van Eekeren N 2018 *Applied Soil Ecology* **125** 26–34
[100] Tilman D and El Haddi A 1992 *Oecologia* **89** 257–264
[101] Langley J A and Hungate B A 2014 *AoB PLANTS* **6** plu035–plu035

[102] Wilson E E and Wolkovich E M 2011 *Trends in Ecology and Evolution* **26** 129–135
[103] Harpole W S, Sullivan L L, Lind E M, Firn J, Adler P B, Borer E T, Chase J, Fay P A, Hautier Y, Hillebrand H, MacDougall A S, Seabloom E W, Williams R, Bakker J D, Cadotte M W, Chaneton E J, Chu C, Cleland E E, D'Antonio C, Davies K F, Gruner D S, Hagenah N, Kirkman K, Knops J M H, La Pierre K J, McCulley R L, Moore J L, Morgan J W, Prober S M, Risch A C, Schuetz M, Stevens C J and Wragg P D 2016 *Nature* **537** 93–96
[104] Murphy G E P and Romanuk T N 2014 *Ecology and Evolution* **4** 91–103
[105] Eskelinen A and Harrison S P 2015 *Proceedings of the National Academy of Sciences* **112** 13009–13014
[106] Harpole W S and Tilman D 2007 *Nature* **446** 791–793

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Differential ecomorphic analysis of urban park vegetation

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Differential ecomorphic analysis of urban park vegetation

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Abstract. The ecomorphic approach was developed to analyze the structure of natural plant communities. This method was applied to analyze the ecological structure of an artificial park plantation in an urban environment. Urban parks perform important and diverse functions in the urban environment. As anthropogenic objects, urban parks should be subject to adequate and effective management that can increase the functional value of forest plantations in the city and ensure their sustainability. In this regard, the choice of the quantitative parameters of the park plantation to be managed is crucial. We hypothesize that ecomorphic analysis can be the basis for selecting optimal quantitative criteria for parkland management. Therefore, the goal of our study was to assess the informational value of ecomorphic analysis for characterizing park plantation in urban environments. In the park, 166 species of vascular plants were found, which are represented by phanerophytes (19.9%), nannophanerophytes (8.4%), hemicryptophytes (40.4%), geophytes (11.4%), theorophytes (18.7%) and geolophytes (1.2%). Sylvants (35.5%) predominate among the coenomorphs, with slightly less pratants (22.3%), ruderants (18.7%) and stepants (14.5%). Cultivants (3.0%), psammophytes (3.0%) and paludants (3.0%) were occasionally found. The proportion of xeromesophytes and mesophytes was the highest (32.5 and 31.3% respectively). The proportion of mesoxerophytes was also relatively high (28.3%). The proportion of other hygromorphs was relatively low. The trophomorphs were represented mainly by mesotrophs (71.1%) and a slightly smaller proportion of megatrophs (22.3%). The oligotrophs were found occasionally (6.6%). Sciogeophytes (57.2%) and heliophytes (30.1%) prevailed among heliomorphs. The proportion of sciophytes and heliosciophytes was much lower (3.6 and 9.0 %, respectively). Entomophilous plant species were the most common among the vegetation cover of the park (71.7%). Anemophilous plants were significantly inferior to them (26.5%). Autogamous and hydrophilous plants were found occasionally (1.2 and 0.6% respectively). Ballistic diasporeochores prevailed among diasporeochores (39.8%). The proportion of anemochores and endozoochores was somewhat lower (27.7 and 12.0% respectively). The results obtained allow to discover the essential ecological features of the park plantation. The park plantation has many features that bring it closer to natural forests. The similarity consists in a significant proportion of silvants, shade-loving species, and mesotrophs. A significant level of anthropogenic impact can be diagnosed on the basis of information about the increased proportion of ruderants in the plant community. The differential analysis of the ecomorphic structure in the section by climorphs is of considerable value. This approach allowed to detect an increased role of the zoogenic factor in the distribution of diaspores of phanerophytes and nannophanerophytes and an increased role of wind in the dispersal of geophytes and therophytes. The role of wind is reduced in the dispersion of hemicryptophytes in the urban environment.

1. Introduction

The urban environment indirectly affects the formation of flora by changing the living conditions. There is also a direct impact through the physical destruction of plants, turning the flora into a variegated conglomerate of elements of both local and alien origin [1, 2]. Urban flora is a set of species that exist independently in the urban area. From the point of view of modern floristics it is a local flora or elementary flora of the regional level [3]. Hemeroby is the resilience of plants and their response to anthropogenic impact. From this point of view, there are two main categories [4–6]. Hemerophiles are species that respond positively to anthropogenic interference and increase their number in its presence [7]. Hemerophobes are species with a strongly negative reaction to anthropogenic factors [8–11]. A more detailed classification is also used [12], which includes the following categories. Agemerobic species are unstable to the impact of urbanization. Frequently these are forest and marsh species, which for various reasons are not adapted to life in urban conditions. Oligogemerobic species are weakly resistant. Mesohemerobic species are moderately resistant, withstand extensive anthropogenic impact. Intensive anthropogenic impact can be withstood by β-euhemerobic species. In turn, α-euhemerobic species inhabit meadows that are fertilized or in highly degraded forests and field weeds. Polyhemerobic species are typical ruderal plants, and metahemerobic species live in completely disturbed habitats [13, 14].

There are four most important types of factors of anthropogenic impact on the living ground cover in recreational forests. Mechanical damage (up to complete destruction) when trampling the ground organs of plants, including renewal buds. The least protected plants with tall succulent shoots and renewal buds located above the soil surface or at its surface suffer the most. Relatively more resistant are species with rosette arrangement of leaves, low elastic shoots, with sufficiently protected buds of renewal. Changes in physical parameters of the soil – moisture, aeration, density, temperature, etc. [15]. As a result, the normal functioning of underground plant organ systems is disrupted. In this case, the nature of underground organs is of great importance: the depth of their penetration and distribution in the soil profile, strength, etc. Cutting off ground shoots and digging up plants that attract the attention of recreationists with their decorative effect. At the same time, generative shoots of flowering plants are particularly affected, which inhibits the process of natural reproduction of the species' cenopopulation. Berry picking, harvesting of food or medicinal raw materials. Obviously, the last type of anthropogenic impact with rare exceptions (for example, mass harvesting of cranberries) does not have a decisive impact on forest ecosystems of urbanized areas. However, it is impossible not to take into account the existence of this factor.

Stress is a process of internal changes in the body systems in response to any strong or prolonged environmental impact [16, 17]. There is a broader interpretation of this term. Stress is a nonspecific response of the organism to any requirement presented to it, accompanied by the restructuring of protective forces [18]. From the point of view of this concept, the change in the nature of plant growth and development can be considered as an adaptation syndrome, which characterizes the degree of restructuring of the plant organism under the influence of anthropogenic pressure, as a compensatory reaction, on the one hand, to the deterioration of living conditions, and on the other hand, to reduce the intensity of competitive relations. The adaptation syndrome is a combination of three phases [19]. The phase of the primary stress reaction is a signal to activate the body's defenses. The phase of adaptation, or resistance, occurs during prolonged exposure to a factor that can cause stress. The degree of stress effect is determined by the level of restructuring of the organism – the more significant the impact, the more the organism changes. At this stage, plants show different forms of growth, can increase the intensity of growth and reproduction. The phase of exhaustion, which occurs after prolonged exposure to the stimulus, when the body loses the achieved adaptation. Reduction of resistance to the source of stress is expressed in a decrease in the size of individuals, in reducing the intensity of their growth and reproduction. Ultimately, the plant may die. The duration of a particular phase is determined by the adaptive capabilities of the species. In some species the stage of depletion occurs quite quickly, in others the phase of adaptation is relatively long. Species with greater plasticity are more stable. An expressive indicator of the state of a species is the type of its cenopopulation in a particular community, determined by the ratio of individuals of different age groups – the age spectrum [20].

Woody plants in urban areas can grow in various kinds of green spaces (in yards among residential buildings, on streets and highways, in squares, gardens and parks, in forest parks and in so-called urban forests) [21–24]. Forests in urbanized areas perform a variety of functions: environmental, sanitary and recreational [25–28]. The forest plantations have a positive impact on the atmosphere and climate of the city. They are able to change air temperature, illumination, wind speed, etc. Of course, this impact is more significant, the better the preservation of plantations [25, 29]. The forest transforms various climatic components while changing the radiation regime to the greatest extent [30–32]. Under the forest canopy, the illumination is much less, and in different types and in different parts of the forest it is different, because the composition of the rocks, the light permeability of the canopy, and the completeness of the stand differ. The total radiation is sharply reduced, because a significant part of it is intercepted by the crowns of trees and shrubs [33, 34]. The lighting becomes very variegated, which depends not only on the tree and shrub canopy, but also on the movement of the sun during the day, on the swaying of trees by the wind, on cloudiness [35]. The changes occur throughout the growing season due to the onset of different phenological phases [36]. At the same time, each type of forest has its own specifics, primarily due to the unifier species and the structure of the ecosystem. In artificial plantations (forest crops), the main species and planting density have a decisive influence on the light regime [37,38]. Wind speed is decreasing in the forest [39]. Inside the forest, at a distance of 30–50 m from the edge of the forest, the wind speed decreases to 30–40%, at a distance of 120–240 m, there is complete calm, especially if there is undergrowth in the plantation [40]. In summer, in cloudless and calm weather, in the contact zone between the city and neighboring green spaces, there is often a so-called breeze is a local breeze directed from the forest towards the city buildings during the day, and at night it blows in the opposite direction [41]. It is able to reduce the air temperature by several degrees. The reason for its occurrence is the difference in the thermal regime of the forest and urban development. As a result of this movement, the air in the city is cleaned and humidified, which also contributes to the improvement of the ecological situation [42, 43].

Urban green spaces and suburban forests play an important, though not decisive role in maintaining the stability of the atmospheric gas composition [44]. The amount of carbon monoxide absorbed by the green mass and the amount of oxygen released by it depend on the condition of the plantation, its age, species composition, completeness and a number of other factors [45]. Green spaces serve as a reliable filter that cleans the air from dust [46]. In the forest, dust particles settle on trunks and branches, on the surface of leaves, stick to resinous secretions. The efficiency of dust collection is determined by the structure of plantations and their species composition [47]. The leaf surface is of great importance. Dust is retained more on rough, pubescent or sticky leaves than on smooth leaves, and even more so on needles. Small leaves usually trap dust better than large ones. Leaves of complex configuration clean the air more efficiently. On average, 1 hectare of forest can retain from 30 to 70 tons of dust. Multi-tiered plantations are more effective than single-tiered ones, deciduous forests are more effective than coniferous ones, but conifers retain their dust trapping functions all year round [48].

Forests clean the air from industrial and transport emissions, which are often toxicants [49]. Among them is sulfur dioxide, which can cause serious damage to the human respiratory system. On average, 1 hectare of forest can annually retain up to 400 kg of this compound. Lead emissions contained in exhaust gases are very dangerous for human health. Lead in particularly large quantities accumulates in plants growing in the immediate vicinity of transport routes. Sharp-leaved maple and small-leaved linden are among the tree species that accumulate toxic substances in the largest quantities. Coniferous species such as pine, spruce and larch are highly sensitive to toxicants [50–52].

Noise is a negative factor in a big city [53, 54]. The constant exposure to noise can lead to the development of neuroses, insomnia, hypertension, reduced performance, especially in older people. Forest plantations dampen sound waves, eliminate the most harmful high-frequency sounds and reduce noise levels. The level of noise pollution reduction depends on the density of crowns, the structure of plantations, their species composition. The most effective in noise absorption are sharp-leaved maple, poplar, linden, oak, elm, birch; a little less effective are coniferous stands. Mixed plantations with shrubs growing under the trees have the best screening properties. The loose soil surface also increases the noise absorption potential of the forest [55, 56]. Plants secrete phytoncides – volatile or water-soluble substances that can destroy pathogens or delay their development. The activity of phytoncides is closely connected with the species composition and age of plantations, with the physiological state of trees, with the season, time of day and many other factors. It is established that for most people, 5–7-hour stay in the forest improves tone and well-being. However, negative feelings may also appear. For example, a high content of turpentine vapors in a coniferous forest on a hot sunny day can worsen the condition of people suffering from cardiovascular diseases; it is better for them to rest in oak forests [57]. Recreation is one of the factors of forest formation, which often has a rather negative impact on forest ecosystems [58, 59].

2. Research aim and objectives

Thus, urban parks perform important and diverse functions in the urban environment. As anthropogenic objects, urban parks should be subject to adequate and effective management that can increase the functional value of forest plantations in the city and ensure their sustainability. In this regard, the choice of the quantitative parameters of the park plantation to be managed is crucial. We hypothesize that ecomorphic analysis can be the basis for selecting optimal quantitative criteria for parkland management. Therefore, the goal of our study was to assess the informational value of ecomorphic analysis for characterizing park plantation in urban environments.

3. Material and methods

3.1. Data collection

The study was carried out in the recreational zone of the Botanical Garden of Dnipro National University named after Oles Gonchar, Dnipro City, Ukraine (48.43°N 35.05°E). The urban park was created after World War II on the site of a natural thermophilous oak forest [60,61]. Vascular plant species lists were recorded for 3×3 m sampling point, along with a visual assessment of species coverage using a Braun-Blanquet scale [62]. The projective cover of plant species was measured at soil level, understory (up to 2 m in height), and canopy (above 2 m in height). All species were identified to species level at all sites. Plant taxonomy is based on Euro+Med Plantbase (https://europlusmed.org/).

3.2. Ecomorphes

Belgard [63] created a typology of forests of the steppe zone of Ukraine in the late 40s of the last century, which is a vivid example of the effectiveness of the application of the principles of biogeocenology and in this sense, this concept should certainly be recognized as structuralist. The typology was supplemented by the system of plant ecomorphs. According to the ideas of Belgard, the ecomorph reveals the relationship between organisms and the environment and reflects the adaptation of individual plant species to the most important elements of biogeocenosis: to the phytocenosis as a whole and to each of the structural elements of the ecotope (thermotope, heliotope, trophotope, hygrotope, thermotope) separately. Any system of life forms (biomorph, ecomorph) has the following broad philosophical basis [64]: a) plants have different ecological amplitudes, i.e. they are more or less limited in their ability to tolerate different environmental conditions; b) there is often a correlation between morphology and adaptation; c) a plant in its successful existence represents what can be called an automatic physiological integration of all factors of its environment. The term ecomorph is preferred because the life form usually refers to adaptations that are expressed in the appearance of the plant, while adaptations not to all structural elements of the biogeocenosis have physiognomic manifestation. Belgard considered ecotope as a combination of climatope and edatope (or edaphotope). He divided climatop into thermotop and heliotop (space factors), edatop (or edaphotop) is divided into trophotop and hygrotop (terrestrial factors).

3.3. Coenomorphes
The plant coenomorph characterizes the adaptation of a living organism to the biogeocenosis as a whole. The plants of the steppe zone of Ukraine are represented by the following coenomorphs:

1) stepants (St) are steppe plants;
2) sylvants (Sil) are forest plants;
3) ruderants (Ru) are plants of weed communities;
4) psammophytes (Ps) are plants of sandy communities;
5) pratants (Pr) are meadow plants;
6) paludants (Pal) are plants of marsh plants;
7) petrophytes (Ptr) are rock plants;
8) halophytoids (Hald) are plants of salt marshes;
9) halophytes (Hal) are plants of salt marshes;
10) calcophytes (Clc) are plants of communities of chalk outcrops;
11) chasmophytes (Chs) are plants of communities of gravelly outcrops;
12) aquants (Aq) are aquatic plants
13) culturants (Cul) are cultivated plants.

In other geographical zones, such coenomorphs as tundrants (Tn) are tundra plants, montants (Mont) are mountain plants, littorants (Lit) are littoral plants on the sea coasts, desert plants (Ds) are desert plants can also be distinguished.

The forest species include the most typical species that make up forest communities. In addition to woody and shrubby plants, sylvants also include grasses, mosses and lichens, which are closely related to the forest environment. Stepants are represented mainly by herbaceous species, as well as some shrubs, mosses and lichens. The vast majority of steppe species are drought-resistant and light-loving, preferring soils with neutral or slightly alkaline reaction. The meadow species (pratans) are herbaceous perennial mesophytes. Pratants differ from forest species by their light ecology. The forest grasses also disappear after the destruction of the forest canopy, and meadow grasses, on the contrary, develop more rapidly. Paludants include mainly herbaceous and moss species that grow in conditions of excessive moisture. Halophytes include semi-shrubs and herbaceous species that live on saline soils and are characterized by light-loving and, as a rule, significant osmotic pressure of cell sap. Ruderants are weeds with diverse ecological properties and usually gravitate to soils with high nitrogen content.

3.4. Terrestrial and cosmic factors

Along with coenomorphs, other ecomorphs are distinguished by the criterion of adaptation to the most essential environmental factors. According to Williams [65], the factors of life of green plants should be divided into two groups:

1) cosmic factors are light and heat;
2) terrestrial factors are water and food.

Therefore, Belgard's system distinguishes ecological groups of plants similar in adaptation to certain cosmic factors:

1) climamorphs are adaptations to climate conditions in general;
2) heliomorphs are adaptations to lighting conditions;
3) thermomorphs are adaptations to the conditions of thermal climate regime.

And ecological groups of plants are similar in adaptation to certain terrestrial factors:

1) trophomorphs are adaptations to soil fertility conditions
2) hygromorphs are adapted to the conditions of humidity regime.

3.5. Climamorphs

Belgard used Raunkiaer life forms [66, 67] as climamorphs: phanerophytes, chameophytes, hemicryptophytes, cryptophytes (geophytes, hydrophytes), therophytes, epiphytes. When choosing the features of life forms for recognition and classification of relationships between plant life and climate, Raunkiaer was guided by three basic rules: a) the feature must be structural and essential; it must represent an important morphological adaptation; b) the trait must be obvious enough to be easily seen in nature to which life form the plant belongs; c) all the life forms used must be of such a nature that they constitute a homogeneous system; they must represent a single viewpoint or aspect of the plants and thus enable comparative statistical treatment of the vegetation of different regions.

Considering these requirements, Raunkiaer differentiated life forms according to the type and degree of protection provided to the growth points of perennial buds, which are responsible for recovery after an unfavorable season. With the exception of some tropical climates that are constantly warm and humid, all of them show a certain seasonal rhythm with alternating periods that are favorable or unfavorable for growth. When comparing two climates, the difference between them in the favorable season may be relatively small, while the differences in the unfavorable season can be significant and of great importance. The unfavorable seasons may be caused by cold or drought, or both, they may be short or long, they may be one or two per year, but it is likely that those structural differences between plants that allow them to survive the unfavorable seasons are a good indicator of the plant climate. Based on these facts, Raunkiaer developed his classification of life forms, which depends primarily on the degree of protection provided to the perennial bud. The system consists of the following five main classes, arranged in accordance with the increased protection of the buds: phanerophytes, chameophytes, hemicryptophytes, cryptophytes and therophytes. Raunkiaer believed that life forms are formed historically as a result of adaptation of plants to climatic conditions of the environment. The percentage distribution of species by life forms in plant communities in the study area is called the biological spectrum. Biological spectra for different physiographic zones and countries serve as indicators of climatic conditions. Raunkiaer classified plants according to where the growing point is located in less favorable seasons, provided that the plant retains the ability to survive these difficult conditions. Depending on the place on Earth, this unfavorable period can be, for example, in the cold winter period or in the dry summer time. In temperate regions, the growth point during the unfavorable season corresponds mainly to winter buds.

3.6. Trophomorphs
Among trophomorphs are distinguished:

1) oligotrophs (OgTr) are adapted to poor soils;
2) mesotrophs (MsTr) are adapted to moderately rich soils;
3) megatrophs (MgTr) are adapted to rich soils;
4) alkalitrophs (AlkTr) are plants of saline physiologically poor soils;
5) parasitic plants (Par), semiparasitic plants (S/par), saprophytes (Sapr) and calciphiles (Ca).

3.7. Hygromorphs
Among hygromorphs are distinguished:

1) euxerophytes (EuKs) are highly drought-resistant species;
2) xerophytes (Ks) are drought-resistant species;
3) mesophytes (Ms) are plants of moderate moisture environment;
4) hygrophytes (Hg) are amphibious species;
5) pleistophytes (Pl) are aquatic plants with floating leaves;
6) hydatophytes (Hy) are plants completely immersed in water.

The transitional forms can be named through the combination of two hygromorphs that are located next to each other. In this case, the leading mode is denoted by the second one, and the auxiliary mode is denoted by a prefix, for example: xeromesophytes – mesophytes that are more drought-resistant than ordinary mesophytes, or: mesohygrophytes – hygrophytes that are able to exist in more arid conditions.

3.8. Moisture variability
The ecological analysis of floodplain ecosystems cannot be complete without taking into account the floodplain factor. Therefore, it is necessary to distinguish between floodplain ecomorphs, namely:

1) extra-floodplain species – occur mainly outside the floodplain;
2) short floodplain – characteristic of floodplains where the flood lasts no more than 10 days
3) medium floodplain – species can withstand floods that last no more than 40 days;
4) long floodplain – withstand floods that last more than 40 days.

The duration of the flood depends on the size of the river: in small rivers it lasts no more than 10 days, in large rivers the flood can last more than 40 days. The number of species that are able to adapt to flooding decreases in proportion to its intensity. Therefore, the species diversity of floodplain communities decreases from short floodplain ecosystems to long floodplain ecosystems. Therefore, the diversity of plant communities in short floodplain ecosystems of small rivers is higher than in long floodplain ecosystems of large rivers.

3.9. Heliomorphs
Among heliomorphs are distinguished:

1) heliophytes (He) are light-loving species;
2) scioheliophytes (ScHe) are light-tolerant species;
3) heliosciophytes (HeSc) are shade-tolerant species;
4) sciophytes (Sc) are shade-loving species.

3.10. Thermomorphs

Among thermomorphs are distinguished:

1) microtherms (MT°) are species originating from the polar geographical climatic zone;
2) mesotherms (MsT°) are species originating from the temperate zone;
3) megatherms (MgT°) are species originate from subtropical or tropical zones;
4) eurytherms (EuT°) are species that can grow in almost all climatic zones of the Earth.

3.11. Generative ecomorphs

These ecomorphs mainly reflect adaptation to growth conditions, so they can be called vegetative. Along with vegetative ecomorphs, there are generative ecomorphs, which characterize the attitude of species to pollination and spread of diasporas. The problem of creating a system of generative ecomorphs was solved by Tarasov [68].

Pollenochores are groups of plants that are distinguished by the type of pollination (for spore plants – by the type of gamete transfer). Among them are distinguished:

1) autogamy plants (Ah) – self-pollinated;
2) hydrophilous plants (Hdph) – pollination is carried out with the help of water;
3) gametohydrophilous plants (Hdgph) – gamete transfer occurs in the aquatic environment;
4) anemophilous plants (Anph) – pollen is distributed by wind;
5) entomophilous plants (Ent) – pollen is distributed by insects;
6) protandrous plants (Pa) – earlier maturation of pollen compared to the stigmas of pistils in plant flowers. It is an adaptation to cross-pollination.
7) protogynous plants (Pg) – earlier maturation of stigmas in the flowers of plants compared to pollen.

Diasporochores (ecobiochores) is a group of plants that are distinguished by the types of plant diaspora dispersal. According to the ways of diaspore dispersal, they are distinguished:

1) endozoochory (EndZ) – transfer of seeds by animals after eating and defecation;
2) synzoochory (SynZ) – transfer of plant fruits by animals when they harvest stocks.
3) myrmekochory (Myrm) – transfer is carried out by ants;
4) epizoochory (EpZ) – transfer on the surface of animals, diaspores are tenacious;
5) anemochory (Anch) – spreading of seeds, fruits and plant spores by air;
6) hydrochory (Hdch) – diaspores are transported by water;
7) autochory (Ach) – self-dispersing plants spread fruits, seeds, spores and vegetative parts of the plant organism with the help of the plant itself without the action of external agents; distinguish between active seed dispersal from a cracked ripe fruit (mechanochory), burying of fruits in the soil (geocarpy), shedding of fruits and seeds only under the influence of gravity (barochory);
8) barochory (Bar) – a kind of autochorus, shedding of fruits and seeds only under the influence of gravity;
9) ballistochory (Bal) – diaspores are scattered by elastic stalks when shocked;
10) geochory (Gch) – diaspores crawl and burrow into the ground, changing their shape;
11) cryptogeochory (KrGch) – hidden geochorus;
12) pervolvent (Perv) – movement of a plant under the influence of wind due to its rolling (tumble-field);
13) anthropochory (Antrch) – spreading of seeds, fruits and plant spores by humans.

4. Results

4.1. Climamorphs

In the park, 166 species of vascular plants were found, which are represented by phanerophytes (19.9%), nannophanerophytes (8.4%), hemicryptophytes (40.4%), geophytes (11.4%), theorophytes (18.7%) and geolophytes (1.2%) (figure 1). *Acer negundo* L., *Acer platanoides* L., and *Robinia pseudoacacia* L. were the most common among phanerophytes. Among nannophanerophytes, *Parthenocissus quinquefolia* (L.) Planch. and *Sambucus nigra* L. were the most common. The most numerous among hemicryptophytes were *Alliaria petiolate* (M.Bieb.) Cavara et Grande, *Anthriscus sylvestris* (L.) Hoffm., *Chelidonium majus* L., *Geum urbanum* L., and *Viola odorata* L.. Among therophytes the most numerous were *Galium aparine* L., *Impatiens parviflora* DC., *Stellaria media* (L.) Vill. Among geophytes the most numerous were *Cirsium arvense* (L.) Scop. and *Humulus lupulus* L. Helophytes were represented by only two species – *Phragmites australis* (Cav.) Trin. ex Steud. and *Sium latifolium* L..

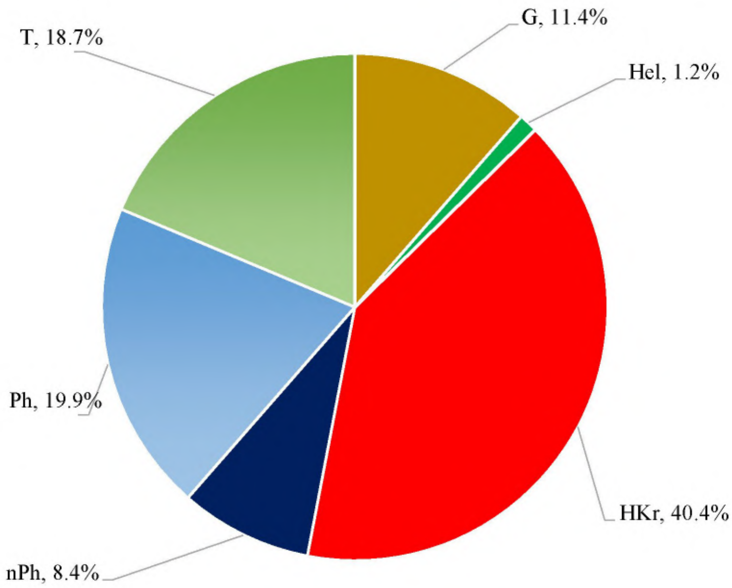

Figure 1. Structure of life forms according to Raunkier (climamorphs): Ph is phanerophyte; nPh is nannophanerophyte; Ch is chameophyte; HKr is hemicryptophyte; T is therophyte; G is geophyte, Hel is helophyte.

4.2. Coenomorphs

Sylvants (35.5%) predominate among the coenomorphs, with slightly less pratants (22.3%), ruderants (18.7%) and stepants (14.5%). Cultivants (3.0%), psammophytes (3.0%) and paludants (3.0%) were occasionally found. Sylvants prevail among phanerophytes (figure 2). The proportion of sylvants among nannophanerophytes was also high. The proportion of stepants, which varied in the range of 12.9–21.4% was established for nannophanerophytes, hemicryptophytes, geophytes and therophytes. The pratants dominated among hemicryptophytes (35.8%). The ruderants dominated among therophytes and geophytes (31.6 and 45.2% respectively). Helophytes were represented by paludants. The highest coenomorphic diversity was found for hemicryptophytes (2.24), with a slightly lower diversity for therophytes and geophytes (2.02 and 2.26, respectively). The lowest coenomorphic diversity was characteristic of phanerophytes and nannophanerophytes. Naturally, the diversity of helophytes,

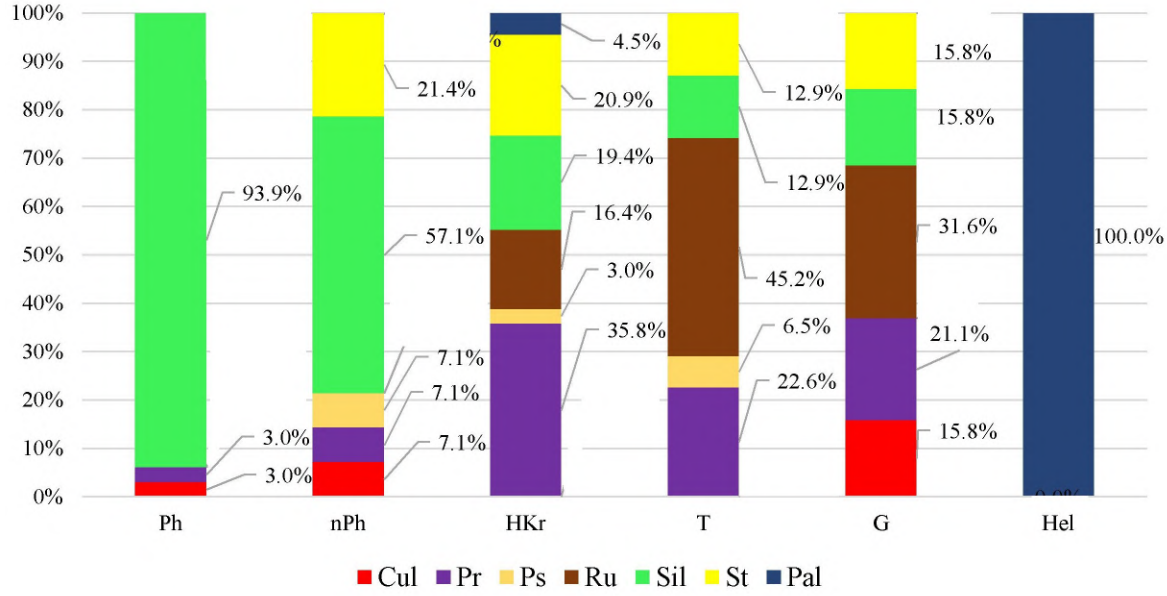

Figure 2. Structure of coenomorphs: Cul are culturants; Pr are pratants; Pal are paludants; Ps are psammophytes (psamants); Ru are ruderals; Sil are silvants; St are stepants. Ceonomorphic diversity: Ph – 0.39, nPh – 1.75, HKr – 2.24, T – 2.02, G – 2.26, Hel – 0. Specific diversity: Ph – 0.08, nPh – 0.46, HKr – 0.37, T – 0.41, G – 0.53, Hel – 0.

which are represented by only two species, was equal to zero. The lowest specific diversity was characteristic of phanerophytes, and the highest was characteristic of geophytes.

4.3. Hygromorphs

The proportion of xeromesophytes and mesophytes was the highest (32.5 and 31.3% respectively). The proportion of mesoxerophytes was also relatively high (28.3%). The proportion of other hygromorphs was relatively low. The hygromorphic structure of phanerophytes and nannophanenophytes was almost identical. These climamorphs were represented mainly by the mesophytes. The hygromesophytes were represented among hemicryptophytes and geophytes (6.0 and 10.5 % respectively). The therophytes were characterized by a low proportion of mesophytes due to the increase in the proportion of xeromesophytes. The helophytes were represented by the hygrophytes and mesohygrophytes. The hygromorphic diversity was the highest among hemicryptophytes, and the lowest among therophytes and helophytes. The lowest specific diversity was typical for phanerophytes, and the highest was typical for geophytes. The specific diversity of climamorphs showed no significant differences.

4.4. Trophomorphs

The trophomorphs were represented mainly by mesotrophs (71.1%) and a slightly smaller proportion of megatrophs (22.3%). The oligotrophs were found occasionally (6.6%). The proportion of megatrophs was the highest among phanerophytes (30.3%) and hemicryptophytes (26.9%) (figure 4). Accordingly, these climamorphs were the most demanding to soil fertility. The proportion of oligotrophs was the highest in nannophanerophytes (14.3%). The helophytes were represented exclusively by the mesotrophs. The level of trophomorph diversity was at the same level for all climamorphs, except for helophytes.

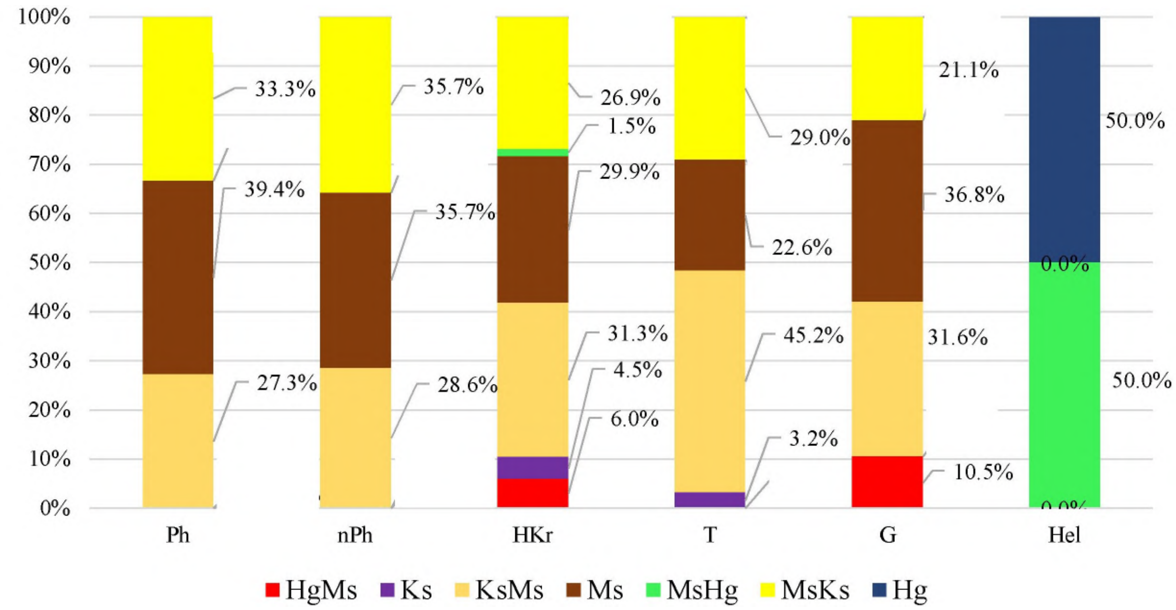

Figure 3. Structure of hygromorphs: Ks are xerophytes; MsKs are mesoxerophytes; KsMs are xeromesophytes; Ms are mesophytes; HgMs are hygromesophytes, MsHg are mesohygrophytes. Hygromorphic diversity: Ph – 1.57, nPh – 1.58, HKr – 2.09, T – 1.68, G – 1.87, Hel – 1. Specific diversity: Ph – 0.31, nPh – 0.41, HKr – 0.34, T – 0.34, G – 0.44, Hel – 1.

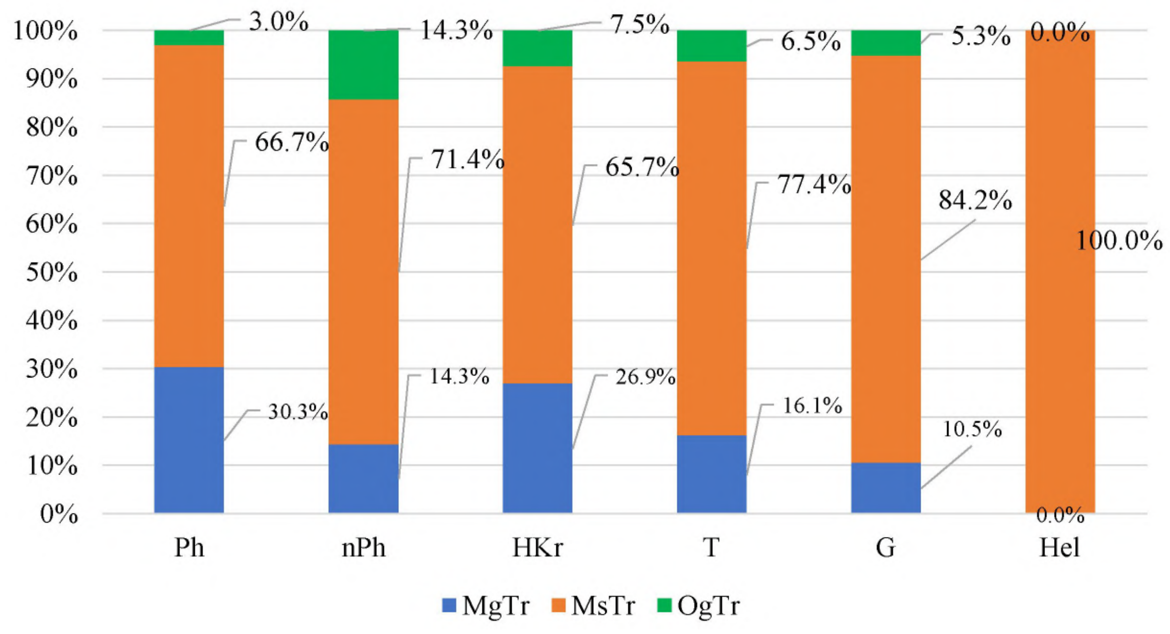

Figure 4. Structure of trophomorphs: MgTr are megatrophs; MsTr are mesotrophs; OgTr are oligotrophs. Trophomorphic diversity: Ph – 1.06, nPh – 1.15, HKr – 1.19, T – 0.97, G – 0.77, Hel – 0. Specific diversity: Ph – 0.21, nPh – 0.3, HKr – 0.2, T – 0.19, G – 0.18, Hel – 0.

The greatest diversity was typical for the hemicryptophytes. The lowest specific diversity was characteristic of the geophytes, and the highest was characteristic of the nannophanerophytes.

4.5. Heliomorphs

Sciogeophytes (57.2%) and heliophytes (30.1%) prevailed among heliomorphs. The proportion of sciophytes and heliosciophytes was much lower (3.6 and 9.0 %, respectively). The proportion of heliophytes was the highest among terophytes, geophytes and helophytes (figure 5). The proportion of heliophytes was lowest for nannophanerophytes. The highest proportion of sciophytes was found for hemicryptophytes. Sciophytes should be noted to be also found among the therophytes and geophytes. The highest proportion of heliosciophytes was among phanerophytes. The greatest heliomorphic diversity was typical for the hemicryptophytes. This diversity was also quite high for therophytes and geophytes. Nannophanerophytes were the least diverse in terms of light level preferences. The lowest specific diversity was typical for nannophanerophytes, and the highest was typical for geophytes.

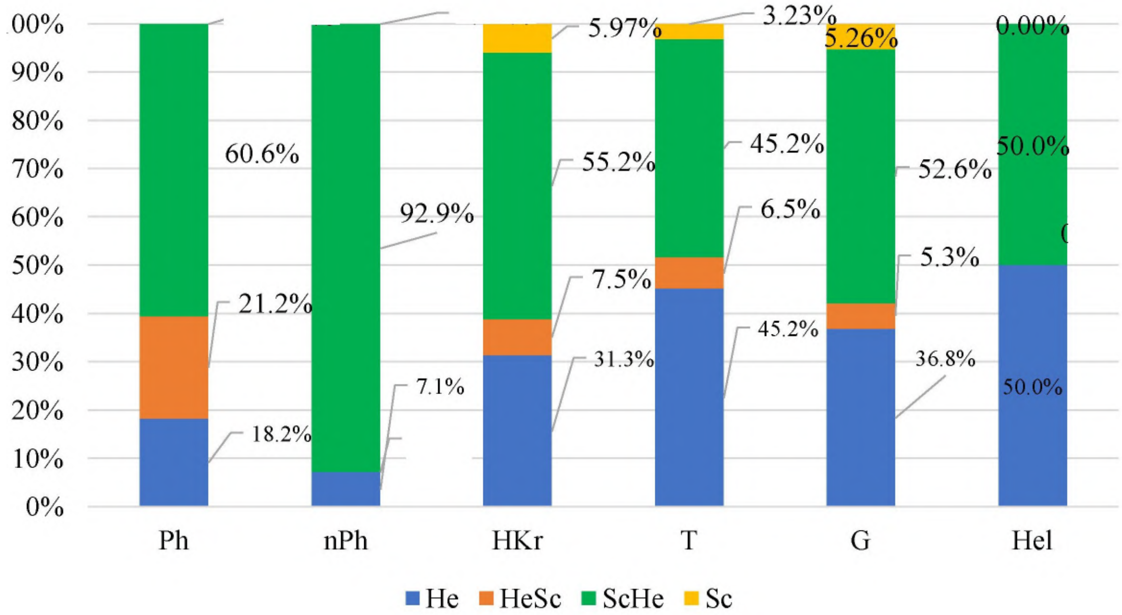

Figure 5. Structure of heliomorphs: HeSc are heliosciophytes; ScHe are scioheliophytes; He are heliophytes, Sc are scioheliophytes. Heliomorphic diversity: Ph – 1.36, nPh – 0.37, HKr – 1.52, T – 1.45, G – 1.47, Hel – 1. Specific diversity: Ph – 0.27, nPh – 0.10, HKr – 0.25, T – 0.29, G – 0.34, Hel – 1.

4.6. Pollenochores

Entomophilous plant species were the most common among the vegetation cover of the park (71.7%). Anemophilous plants were significantly inferior to them (26.5%). Autogamous and hydrophilous plants were found occasionally (1.2 and 0.6% respectively). The entomophilous species were most common among nannophanerophytes (92.9%) (figure 6). The anemophilous species were most commonly found among phanerophytes and helophytes (39.4 and 50.0%, respectively). The hydrophilous species were found among geophytes. The autogamous species were found among therophytes. Pollenochoric diversity was the highest among geophytes. The lowest specific diversity was characteristic of nannophanerophytes, and the highest was characteristic of geophytes.

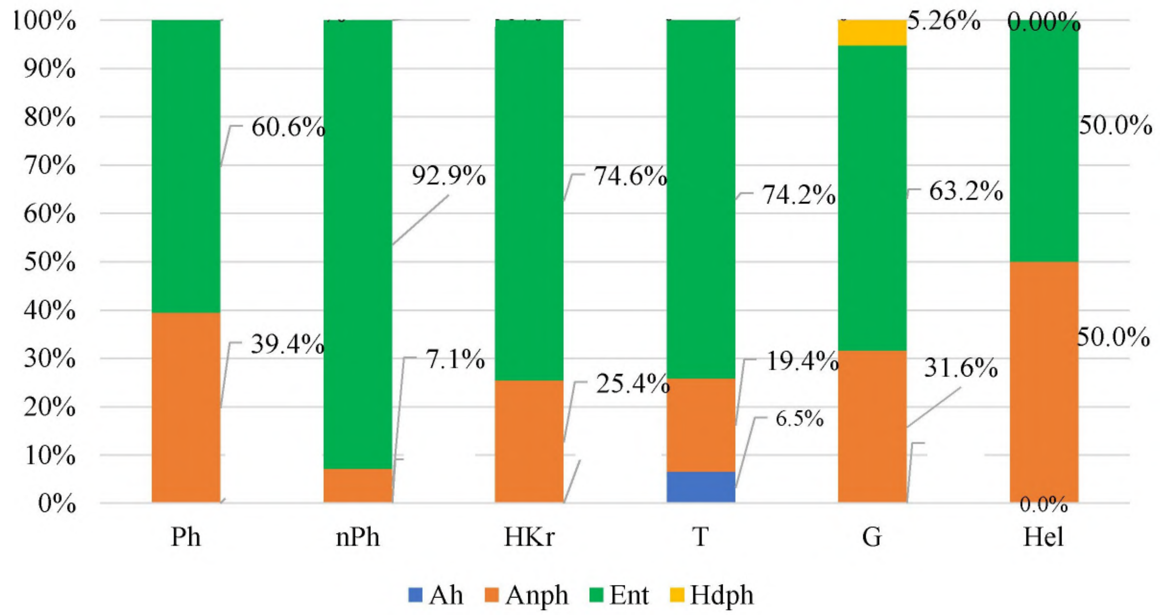

Figure 6. Structure of pollenochorus: Ah are autogamous plants; Anph are anemophiles; Ent are entomophiles, Hdph are hydrophilus plants. Pollenchoric diversity: Ph – 0.97, nPh – 0.37, HKr – 0.82, T – 1.03, G – 1.17, Hel – 1. Specific diversity: Ph – 0.19, nPh – 0.1, HKr – 0.13, T – 0.21, G – 0.27, Hel – 1.

4.7. Diasporochores

Ballistic diasporeochores prevailed among diasporeochores (39.8%). The proportion of anemochores and endozoochores was somewhat lower (27.7 and 12.0% respectively). Other diasproochores accounted for 0.6–4.8 of the total number of species. Endozoochores were mainly found among nannophanerophytes (78.6%). Among phanerophytes, anemochores were mainly found (60.6%). Among herbaceous species, ballistic species prevailed (47.4–56.7%). The highest diasporechoric diversity was found for hemicryptophytes. The lowest specific diversity was characteristic of nannophanerophytes, and the highest was characteristic of geophytes.

5. Discussion

In ecology, there are two alternative perspectives on the nature of ecological communities: continualism and structuralism [69].

Continualism considers the response of an organism to the effects of environmental factors as a species-specific property, which is generally described by a bell-shaped curve [70–72]. Hence, it is natural to conclude about living organisms as indicators of environmental properties, which became the basis for the creation of many indicator scales [73]. One of the first such scales was created by Ramenskiy, the founder of continualism [74]. Other phytoindicator scales differ in their resolution, the list of environmental properties indicated, and the aspect of the species response curve to an environmental factor: whether it is an optimum zone based on which Ellenberg scales are indicated [75–77], or whether it is the range of the factor within which the species can exist, as provided in the range scales of Tsyganov [78] or Didukh [79]. The principles of phytoindication are a practical consequence of biotope theory [80–82] according to which biocenosis [83,84] depends on the observed physical properties of the environment [85–87]. And an ecosystem, in turn, is a combination of biotope and biocenosis. Within the framework of structuralism, environmental factors take a second place and the intrasystem interactions

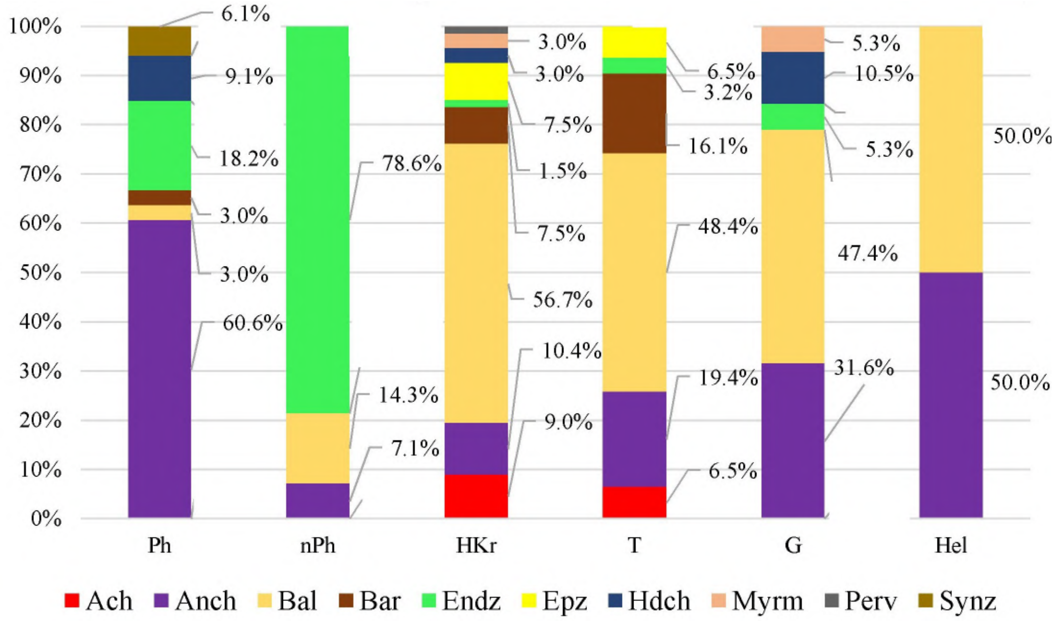

Figure 7. Structure of diasporochores: Ach are autochores; Anch are anemochores; Bal are ballistae; Bar are barochores; Endz are endozoochores; Epz are epizoochores; Hdch are hydrochores; Myrm are myrmecochores; Synz are synzoochores. Diasporochorous diversity: Ph – 1.75, nPh – 0.95, HKr – 2.16, T – 2.06, G – 1.82, Hel – 1. Specific diversity: Ph – 0.35, nPh – 0.25, HKr – 0.36, T – 0.42, G – 0.43, Hel – 1.

are advanced, which leads to explaining the observed boundaries of plant communities as those of an endogenous nature [88]. The most orthodox branch of structuralism is Sukachev's biogeocenology [89–91].

More recently, the conflict between continuism and structuralism has taken the form of a competition between ecological niche theory [92] and neutral diversity theory [93]. The constructive position of this confrontation is to soften the problem, namely, which of the alternative representations is the only true and which is false [94]. The solution moves to the question of under what circumstances one of the views explains a greater range of observable facts than the other, and under what circumstances the priority goes to the competing viewpoint.

Biogeocenosis is a combination of biocenosis and ecotope [91]. The term ecotope was coined by Vysotsky [95], but in English-language literature Sørensen [67] or Tansley [96] are considered as its authors. An ecotope is the smallest unit of the Earth's surface that possesses homogeneity of at least one property of the geosphere: atmosphere, vegetation, soil cover, rocks, water, etc., with a non-extreme variation of other properties [97]. Ramensky [98], along with ecotope (habitat), which is determined by direct acting factors (heat, light, aeration, nutrient, soil reaction, salinity), distinguishes entopia (location), which is determined by the indirect topological conditions. In the tradition of biogeocenology, an ecotope includes a climatope and an edaphotope. The climatotope, in turn, consists of a heliotope and a thermotope, and the edaphotope consists of a hygrotop and a trophotope [89]. Sukachev [90] considers a biotope as the zoological equivalent of the botanical term ecotope. However, the history and practice of using these terms allow them to be interpreted as the equivalent of abiotic properties of the environment within the framework of continuism (biotope is a component part of the dimensionless concept of ecosystem) and abiotic properties of the environment transformed by biota (ecotope is a component part of biogeocenosis as ecosystem within the boundaries of phytocenosis) within structuralism. In the late forties of the last century, Belgard [63] created the typology of the forests of the steppe zone of Ukraine, which is a bright example of the effectiveness of the principles of biogeocenology and in this sense this concept should certainly be recognized as structuralist. The typology was supplemented by the system of plant ecomorphs.

According to Belgard's ideas, an ecomorph reveals the relationship between organisms and the environment and reflects the degree of their adaptation to the most important elements of the biogeocenosis. The term ecomorph is preferred because the life form usually refers to adaptations that are expressed in the external form of the plant, whereas adaptations to all structural elements of the biogeocenosis do not have a physiognomic manifestation. The key feature of the Belgrad system of ecomorphs is the coenomorph which is the adaptation of plant species to the phytocoenosis as a whole [99]. The ecomorph system has been extended to other components of the biogeocenosis [100–103], which allows us to interpret coenomorph as adaptation of biotic and bioinert component of biogeocenosis to the biogeocoenosis as a whole. In turn, the adaptivity is defined as the responses of various objects to the environmental factors, which manifests itself in changes in the structure and functions of responding objects and their groups in response to various changing conditions, resulting in the maintenance of their existence [104]. Coenomorphs are distinguished along with adaptations to the most essential environmental factors such as climate (climomorphs), light regime (heliomorphs), thermal regime (thermomorphs), soil fertility (trophomorphs), and moisture regime (hygromorphs) [105]. The boundaries of the gradations of the corresponding factors are determined by the internal integrity of such categories as forest type, which in essence is equivalent to the concept of biogeocenosis type [106]. These gradations were proposed by Matveev [107] to represent in a score form and use for the purpose of phytoindication of the corresponding environmental factors. However, Belgard developed a system of ecomorphs primarily to assess the condition of the biogeocenosis as a whole. The spectra of hygromorphs, trophomorphs, climomorphs, thermomorphs, heliomorphs within a particular coenomorph illustrate the idea that under conditions of varying environmental properties a biogeocenosis can preserve its integrity and identity [108, 109]. Therefore, attempts to interpret coenomorphs as a tool for phytoindication of biotopes [110] are somewhat inconsistent with the purpose of this concept and the nature of ecological groups that are denoted by this term. Assuming that coenomorphs are discrete representations of the ecological continuum of plant organisms, this concept carries no additional information and is therefore degenerate for indicating biotope properties. In such a case, there is no objective criterion for distinguishing coenomorphs and, ultimately, their number and quality can be arbitrary. Often, a concept such as an ecological and cenotic group is used as an equivalent of the term coenomorph, or they refer to the ecological and cenotic relationship of a species. However, such a position is subject to criticism on the basis of the conceptual essence of the term, which implies the conditions of existence of biological objects, rather than their association with something [111]. Therefore, it is critically noted that the floristic studies should either abandon the use of community names to denote the habitat of individuals or their populations at all, or justify the possibility of their use in an ecological sense [112, 113]. If coenomorphs are discrete classes of plant species that are separated from each other to a greater extent than can be assumed based only on the continuum nature of ecological differences between species, then information on the coenomorphic membership of a species and, consequently, the coenomorphic structure of a community, can carry additional information for indicating the properties of an ecotope [114, 115].

Our results indicate a high level of plant community diversity within the city park. The plant community is represented by the different ecological groups. The tree layer is represented by phanerophytes, in the undergrowth predominantly nannophanerophytes are represented. The grass stand is represented by hemicryptophytes, geophytes, therophytes and helophytes. The wide ecological diversity of plant climomorphs in the park plantation indicates a potential for sustainability of this plant complex. On the other hand, the climomorphic structure indicates the presence of a permanent disturbance regime in the park plantation, which manifests itself in an increase in geophytes and thermophytes. It should be noted that the helophytes are represented by only two plant species. In the natural state along the thalweg of the gully, on the basis of which the city park was formed, a stream flowed, so the diversity of helophytes could be much higher. The low diversity of helophytes indicates a significant transformation of the landscape cover of the urban environment.

The ecomorphic analysis is applied to analyze the plant community as a whole. We applied the ecomorphic approach to the differential analysis of plant community climomorphs. The climomorphs were found to differ significantly in their ecomorphic structure. Thus, phanerophytes and nannophanerophytes differ from herbaceous layer plants in their coenomorphic structure. The phanerophytes are expectedly represented by the silvants. The diversity of coenomorphic structure of nannophanerophytes increases due to the growing proportion of steppants. The steppe shrubs usually form marginal complexes of forest communities in steppe, which ensures their ecological stability. An increase in the proportion of steppes among nannophanerophytes can be regarded as an element of maintaining the sustainability of artificial forest plantations in urban environments. Among herbaceous plants, the proportion of steppe and meadow species is systematically high, while the proportion of forest species is insignificant. This structure emphasizes the amphicenotic nature of the plant community structure. The cenotic elements of different nature have priority in different horizontal layers of the community. Among the therophytes, the ruderants predominate. This advantage is carried out against the background of a decrease in the proportion of silvants. Thus, the disturbance of ecological regimes, which provide the forest type of the cycle of substances and energy flow, leads to ruderalization of the ecological environment of the park plantation.

Phanerophytes and nannophanerophytes are represented by the mesoxerophytes, xeromesophytes and mesophytes. In plant layers the proportion of both mesoxerophytic and mesophytic hygromorphs decreases, but the proportion of xeromesophytic hygromorphs increases. This trend should be regarded as a decrease in the tolerance of herbaceous cover to the moisture conditions. The structure of trophomorphs is rather stable in the section of climomorphs. The plant community of the park plantation is mesotrophic.

The plant community is dominated by sociogeliophytes and the highest proportion of this heliomorph is characteristic of nannophanerophytes. The diversity of phanerophytes in comparison with nannophanerophytes increases at the expense of heliophytes, and the diversity of the herbaceous layer increases at the expense of both heliophytes and sociophytes. It is obvious that the forest stand of park plantation forms a wide variety of crown architectonics, which creates conditions for life of both light-loving and shade-loving species of herbaceous plants. A competitive strategy for the tree species is to adapt to the deficit of light under the canopy of other tree species. Obviously, a mosaic of light conditions is a characteristic of park plantings. Continuous park plantation management procedures prevent the development of a dense canopy of woody species that is observed in natural forests.

The predominance of entomophilous plant species in park plantations raises the problem of comprehensive protection of the animal component in urban forests. It is also important to note the potential of the plant community as a factor supporting animal diversity in the urban environment. Significant differences are observed between phanerophytes and nannophanerophytes with respect to diaspore structure. The diaspores of park plantation phanerophytes are distributed predominantly by wind, while the diaspores of nannophanerophytes are distributed predominantly by animals. The phanerophytes of the regional flora are represented by anemochores in 59.6% of cases and by endozoochores in 19.2% of cases, which is fully consistent with the values found in the park plantation. In turn, among phanerophytes in the park, there are almost twice as many synzoochores as in the regional flora (6.1% vs. 3.85%). The endozoochores are also more typical for the park plantation nannophanerophytes than for this climomorph in the regional flora as a whole (78.6% vs. 66.67%). At the same time, the nannophanerophytes of the park plantation are twice as rarely represented by the anomochores as is observed in the regional flora (7.1% vs. 14.6% in the regional flora). Among the hemicryptophytes, the anemochores occur much less frequently than in the regional flora (10.4% vs. 20.8% in the regional flora), whereas among the park's therophytes and geophytes, the anemochores occur more frequently than in the regional flora (19.4% vs. 9.9% in the regional flora for therophytes and 31.6% vs. 20.8% in the regional flora for geophytes). Thus, the park plantation has a specificity of its diaspore structure. It consists in the increased role of zoogenic factor for diaspore dispersal for phanerophytes and nannophanerophytes, the increased role of wind in geophyte and terrorophyte dispersal and the decreased role of wind in hemicryptophyte dispersal.

6. Conclusion

The ecomorphic approach was developed to analyze the structure of natural plant communities. This method was applied to analyze the ecological structure of an artificial park plantation in an urban environment. The results obtained allow to discover the essential ecological features of the park plantation. The park plantation has many features that bring it closer to natural forests. The similarity consists in a significant proportion of silvants, shade-loving species, and mesotrophs. A significant level of anthropogenic impact can be diagnosed on the basis of information about the increased proportion of ruderants in the plant community. The differential analysis of the ecomorphic structure in the section by climorphs is of considerable value. This approach allowed to detect an increased role of the zoogenic factor in the distribution of diaspores of phanerophytes and nannophanerophytes and an increased role of wind in the dispersal of geophytes and therophytes. The role of wind is reduced in the dispersion of hemicryptophytes in the urban environment.

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References

[1] Dyderski M K, Tyborski J and Jagodziński A M 2017 *Urban Forestry and Urban Greening* **27** 76–83 URL https://doi.org/10.1016/j.ufug.2017.06.016
[2] Rejmánek M 2018 *Diversity and Distributions* **24**(1) 129–136 URL https://doi.org/10.1111/ddi.12665
[3] Melnychuk S and Trochymenko G 2017 *ScienceRise: Biological Science* **2**(5) 24–29 URL https://doi.org/10.15587/2519-8025.2017.99760
[4] Battisti C, Fanelli G, Mariani L and Capizzi D 2017 *Ecological Indicators* **76** 178–183 URL https://doi.org/10.1016/j.ecolind.2017.01.014
[5] Rüdisser J, Tasser E and Tappeiner U 2012 *Ecological Indicators* **15**(1) 208–216 URL https://doi.org/10.1016/j.ecolind.2011.09.027
[6] Testi A, Bisceglie S, Guidotti S and Fanelli G 2009 *Aquatic Ecology* **43**(2) 477–486 URL https://doi.org/10.1007/s10452-008-9205-8
[7] Pulev A and Sakelarieva L 2013 *Biodiscovery* (7) URL https://doi.org/10.7750/BioDiscovery.2013.7.3
[8] Klausnitzer B 1983 *Entomologische Nachrichten und Berichte* **27** 241–61
[9] Klausnitzer B 1987
[10] Klausnitzer B 1993
[11] Klausnitzer B and Richter K 1983 *Oecologia* **59**(1) 79–82 URL https://doi.org/10.1007/BF00388077
[12] Frank D and Klotz S 1990 *Biologisch-ökologische Daten zur Flora der DDR* (Halle-Wittenberg, Halle (Saale): Martin-Luther-Universität)
[13] Klötzli F, Peet R and Maarel E 1993 *Journal of Vegetation Science* **4**(1) 1–4 URL https://doi.org/10.1111/jvs.1993.4.issue-1

[14] Mohanty M and Patra H K 2012 *Bioremediation Journal* **16**(3) 147–155 URL https://doi.org/10.1080/10889868.2012.687414
[15] Edmondson J L, Stott I, Davies Z G, Gaston K J and Leake J R 2016 *Scientific Reports* **6** URL https://doi.org/10.1038/srep33708
[16] Aber J, Neilson R, McNulty S, Lenihan J, Bachelet D and Drapek R 2001 *Bioscience* **51**(9) 735–51 URL https://doi.org/10.1641/0006-3568(2001)051[0735:FPAGEC]2.0.CO;2
[17] Williams N S, Schwartz M W, Vesk P A, McCarthy M A, Hahs A K, Clemants S E, Corlett R T, Duncan R P, Norton B A, Thompson K and McDonnell M J 2009 *Journal of Ecology* **97**(1) 4–9 URL https://doi.org/10.1111/j.1365-2745.2008.01460.x
[18] Daev E V 2019 *Ecological genetics* **17**(4) 103–111 URL https://doi.org/10.17816/ecogen174103-111
[19] Aich P, Potter and Griebel 2009 *International Journal of General Medicine* 19 URL https://doi.org/10.2147/IJGM.S4843
[20] Kranner I, Minibayeva F V, Beckett R P and Seal C E 2010 *New Phytologist* **188**(3) 655–673 URL https://doi.org/10.1111/j.1469-8137.2010.03461.x
[21] Brown D G, Johnson K M, Loveland T R and Theobald D M 2005 *Ecological Applications* **15**(6) 1851–1863 URL https://doi.org/10.1890/03-5220
[22] Lian P K and Sodhi N S 2004 *Ecological Applications* **14**(6) 1695–1708 URL https://doi.org/10.1890/03-5269
[23] Planchuelo G, von Der Lippe M and Kowarik I 2019 *Landscape and Urban Planning* **189** 320–334 URL https://doi.org/10.1016/j.landurbplan.2019.05.007
[24] Seto K C, Güneralp B and Hutyra L R 2012 *Proceedings of the National Academy of Sciences of the United States of America* **109**(40) 16083–16088 URL https://doi.org/10.1073/pnas.1211658109
[25] Lal R 2019 *Managing Urban soils for food security and adaptation to climate change* (Springer) p 302–319 URL https://doi.org/10.1007/978-3-319-89602-1_35
[26] Shchepeleva A S, Vizirskaya M M, Vasenev V I and Vasenev I I 2019 *Analysis of carbon stocks and fluxes of urban lawn ecosystems in moscow megapolis* (Springer) p 80–88 URL https://doi.org/10.1007/978-3-319-89602-1_11
[27] Thompson G L and Kao-Kniffin J 2019 *Frontiers in Ecology and Evolution* **7** URL https://doi.org/10.3389/fevo.2019.00315
[28] White M A, Nemani R R, Thornton P E and Running S W 2002 *Ecosystems* **5**(3) 260–273 URL https://doi.org/10.1007/s10021-001-0070-8
[29] Carreiro M M and Tripler C E 2005 *Ecosystems* **8**(5) 568–582 URL https://doi.org/10.1007/s10021-003-0172-6
[30] Simon A, Katzensteiner K and Gratzer G 2019 *Forest Ecology and Management* **453** URL https://doi.org/10.1016/j.foreco.2019.117589
[31] Steinauer K, Zytynska S, Weisser W W and Eisenhauer N 2014 *Pedobiologia* **57**(3) 139–145 URL https://doi.org/10.1016/j.pedobi.2014.01.007
[32] Tosso F, Doucet J L, Daïnou K, Fayolle A, Hambuckers A, Doumenge C, Agbazahou H, Stoffelen P and Hardy O J 2019 *Ecology and Evolution* **9**(23) 13114–13126 URL https://doi.org/10.1002/ece3.5740
[33] Gossner M M 2009 *European Journal of Entomology* **106**(2) 241–252 URL https://doi.org/10.14411/eje.2009.032
[34] Hubbell S P, Foster R B, O'Brien S T, Harms K E, Condit R, Wechsler B, Wright S J and Loo De Lao S 1999 *Science* **283**(5401) 554–557 URL https://doi.org/10.1126/science.283.5401.554
[35] Wirth R, Herz H, Ryel R J, Beyschlag W and Hölldobler B 2003 *Forest Light Regimes* p 61–69 URL https://doi.org/10.1007/978-3-662-05259-4_5
[36] Liang L, Schwartz M and Fei S 2011
[37] Canham C D, Denslow J S, Platt W J, Runkle J R, Spies T A and White P S 1990 *Canadian Journal of Forest Research* **20**(5) 620–631 URL https://doi.org/10.1139/x90-084
[38] Škvareninová J, Tuhárska M, Škvarenina J, Babálová D, Slobodníková L, Slobodník B, Středová H and Minďaš J 2017 *Moravian Geographical Reports* **25**(4) 282–290 URL https://doi.org/10.1515/mgr-2017-0024
[39] Ma K M, Fu B J, Liu S L, Guan W B, Liu G H, Lü Y H and Anand M 2004 *Land Degradation and Development* **15**(1) 75–85 URL https://doi.org/10.1002/ldr.584
[40] Freundorfer A, Rehberg I, Law B E and Thomas C 2019 *Agricultural and Forest Meteorology* **279** 107696 URL https://doi.org/10.1016/j.agrformet.2019.107696
[41] Li X, Koh T, Panda J and Norford L K 2016 *Journal of Geophysical Research: Atmospheres* **121**(9) 4386–4403 URL https://doi.org/10.1002/2015JD024452
[42] Jiao-jun Z, Zu-gen L, Xiu-fen L, Matsuzaki T and Gonda Y 2004 *Journal of Forestry Research* **15**(2) 153–160 URL https://doi.org/10.1007/BF02856753

[43] Kitada T, Okamura K and Tanaka S 1998 *Journal of Applied Meteorology* **37**(10) 1026–1046 URL https://doi.org/10.1175/1520-0450(1998)037<1026:EOTAUO>2.0.CO;2
[44] Rao P, Hutyra L R, Raciti S M and Templer P H 2014 *Biogeochemistry* **121**(1) 229–245 URL https://doi.org/10.1007/s10533-013-9861-1
[45] Arshad M A, Franzluebbers A J and Azooz R H 1999 *Soil and Tillage Research* **53**(1) 41–47 URL https://doi.org/10.1016/S0167-1987(99)00075-6
[46] Lüttge U and Buckeridge M 2020 *Trees* URL https://doi.org/10.1007/s00468-020-01964-1
[47] Xiao Z, Xiong C, Yan C, Yan G, Yang F, Yuan W, Yuan X, Zhang Q, Zhang X, Zhang Z, Zhao P, Zhao X, Zhao X, Zheng Y, Zhou S and Zhu X 2020 *Urbanization: monitoring and impact assessment* (Elsevier) p 833–870 URL https://doi.org/10.1016/B978-0-12-815826-5.00023-4
[48] Suarez-Rubio M and Krenn R 2018 *Journal of Urban Ecology* **4**(1) URL https://doi.org/10.1093/jue/juy027
[49] Livesley S J, McPherson E G and Calfapietra C 2016 *Journal of Environmental Quality* **45**(1) 119–124 URL https://doi.org/10.2134/jeq2015.11.0567
[50] Calfapietra C, Morani A, Sgrigna G, Di Giovanni S, Muzzini V, Pallozzi E, Guidolotti G, Nowak D and Fares S 2016 *Journal of Environmental Quality* **45**(1) 224–233 URL https://doi.org/10.2134/jeq2015.01.0061
[51] Chameides W L, Fehsenfeld F, Rodgers M O, Cardelino C, Martinez J, Parrish D, Lonneman W, Lawson D R, Rasmussen R A, Zimmerman P, Greenberg J, Mlddleton P and Wang T 1992 *Journal of Geophysical Research* **97**(D5) 6037 URL https://doi.org/10.1029/91JD03014
[52] Dunn-Johnston K A, Kreuzwieser J, Hirabayashi S, Plant L, Rennenberg H and Schmidt S 2016 *Journal of Environmental Quality* **45**(1) 234–243 URL https://doi.org/10.2134/jeq2015.01.0051
[53] de Andrade A C, Medeiros S and Chiarello A G 2020 *Mammal Research* **65**(3) 481–491 URL https://doi.org/10.1007/s13364-020-00492-0
[54] De Paiva Vianna K M, Alves Cardoso M R and Rodrigues R M C 2015 *Noise and Health* **17**(76) 125–133 URL https://doi.org/10.4103/1463-1741.155833
[55] Ferrini F, Fini A, Mori J and Gori A 2020 *Sustainability* **12**(10) 4247 URL https://doi.org/10.3390/su12104247
[56] Yang J L, Zhang G L, Shi X Z, Wang H J, Cao Z H and Ritsema C J 2009 *Soil and Tillage Research* **105**(2) 292–299 URL https://doi.org/10.1016/j.still.2009.04.003
[57] Li Q 2010 *Environmental Health and Preventive Medicine* **15**(1) 9–17 URL https://doi.org/10.1007/s12199-008-0068-3
[58] Bonato L and Minelli A 2014 *Zootaxa* **3770**(1) 1–136 URL https://doi.org/10.11646/zootaxa.3770.1.1
[59] Dudek T, Kasprzyk I and Dulska-Jeż A 2018 *European Journal of Forest Research* **137**(6) 849–862 URL https://doi.org/10.1007/s10342-018-1144-x
[60] Goncharenko I and Kovalenko O 2019 *THAISZIA - JOURNAL OF BOTANY* **29**(2) URL https://doi.org/10.33542/TJB2019-2-05
[61] Goncharenko I, Semenishchenkov Y, Tsakalos J L and Mucina L 2020 *Biologia* **75**(3) 337–353 URL https://doi.org/10.2478/s11756-019-00413-w
[62] Westhoff V and Van Der Maarel E 1978 *The Braun-Blanquet Approach* (Dordrecht: Springer Netherlands) p 287–399 URL https://doi.org/10.1007/978-94-009-9183-5_9
[63] Belgard A 1950 *Forest vegetation of South–Eeast part of the Ukraine [Lesnaya rastitel'nost' Yugo-Vostoka USSR]* (Kiev (in Russian): Shevchenko Kiev State University Publishing House)
[64] Cain S A 1950 *The Botanical Review* **16**(1) 1–32 URL https://doi.org/10.1007/BF02879783
[65] Williams V R 1947 *Pedology* (Moscow: Selhozgiz)
[66] Raunkiaer C 1937 *Plant life forms* (Oxford: Clarendon Press)
[67] Sørensen T 1936 *Some ecosystemtical characteristics determined by Raunkiær's circling method* (Helsingfors: Nordiska (19. skandinaviska) naturforskarmöteti) p 474–475
[68] Tarasov V 2012 *Flora of Dnipropetrovsk and Zaporizhia regions* (Dnipropetrovsk: Lira (in Ukranian))
[69] Zhirkov I 2017 *Bio-Geography, general and specialty* (Moscow: KMK Scientific Pres)
[70] Erofeeva E A 2021 *Journal of Forestry Research* **32**(5) 1789–1802 URL https://doi.org/10.1007/s11676-021-01312-0
[71] Gauch H G, Chase G B and Whittaker R H 1974 *Ecology* **55**(6) 1382–1390 URL https://doi.org/10.2307/1935466
[72] Johnson R W and Goodall D W 1980 *Vegetatio* **41**(3) 133–142 URL https://doi.org/10.1007/BF00052442
[73] Kunakh O M and Fedyay I O 2020 *Biosystems Diversity* **28**(2) 195–202 URL https://doi.org/10.15421/012025
[74] Ramenskiy L, Tsatsenkin I, Chizhikov O and Antipin N 1956 *Ecological evaluation of the fodder lands by vegetation cover* (Moscow: Sel'khozgiz)

[75] Diekmann M 1995 *Ecography* **18**(2) 178–189 URL https://doi.org/10.1111/j.1600-0587.1995.tb00339.x
[76] Ellenberg H 1979 *Zeigerwerte der Gefisspflanzen Mitteleuropas* 2nd ed (Göttingen: Scripta Geobotanica)
[77] Ellenberg H, Weber H, Dull R, Wirth V, Werner W and Paulissen D 1991 *Scripta Geobotanica* **18** 1–248
[78] Tsyganov D 1982 *Phytoindication of ecological factors in the subzone of mixed coniferous–broad–leafed forests* (Moscow: Nauka)
[79] Didukh Y P 2011 *The ecological scales for the species of Ukrainian flora and their use in synphytoindication* (Kyiv: Phytosociocenter)
[80] Dahl F 1908 *Zoologischer Anzeiger* **33** 349–353
[81] Newson M D and Newson C L 2000 *Progress in Physical Geography: Earth and Environment* **24**(2) 195–217 URL https://doi.org/10.1177/030913330002400203
[82] Townsend C R and Hildrew A G 1994 *Freshwater Biology* **31**(3) 265–275
[83] Möbius K 1874 *Die Auster und die Austernwirthschaft* (Berlin: Hempel und Parey)
[84] Möbius K 2000 *The Oyster bank is a biocönose, or a social community* (Athens, Georgia, USA: University of Georgia Press) p 111–114
[85] Clifford N J, Harmar O P, Harvey G and Petts G E 2006 *Aquatic Conservation: Marine and Freshwater Ecosystems* **16**(4) 389–408 URL https://doi.org/10.1002/aqc.736
[86] Jowett I G 1993 *New Zealand Journal of Marine and Freshwater Research* **27**(2) 241–248 URL https://doi.org/10.1080/00288330.1993.9516563
[87] Padmore C 1998 *Aquatic Ecosystem Health and Management* **1**(1) 25–35 URL https://doi.org/10.1016/s1463-4988(98)00004-9
[88] Kunah O M, Zelenko Y V, Fedushko M P, Babchenko A V, Sirovatko V O and Zhukov O V 2019 *Biosystems Diversity* **27**(2) 156–162 URL https://doi.org/10.15421/011921
[89] Sukachev V N 1942 *Soviet Botany* **1–3** 5–17
[90] Sukachev V N 1965 *Biology Bulletin* **26**(3) 249–260
[91] Sukachev V N and Dylis N V 1964 *The main concepts of the forest biogeoceonology* (Moscow: Nauka)
[92] Hutchinson G E 1959 *The American Naturalist* **93**(870) 145–159 URL https://doi.org/10.1086/282070
[93] Hubbell S P 2001 *The unified neutral theory of biodiversity and biogeography* (Princeton: Princeton University Press, New Jersey, USA)
[94] Kunakh O N, Kramarenko S S, Zhukov A V, Zadorozhnaya G A and Kramarenko A S 2018 *Ruthenica* **28**(3) 91–99
[95] Vysotsky G N 1925 *Cover science* (Minsk, Leningrad: Main Botanical Garden)
[96] Tansley A 1939 *The British Isles and their vegetation* (Cambridge: Cambridge University Press)
[97] Naveh Z and Lieberman A 1994 *Landscape Ecology: Theory and application* 2nd ed (New York: Springer-Verlag)
[98] Ramensky L G 1938 *Introduction to Comprehensive Soil and Geobotanical Investigations of Land* (Moscow: Sel'khozgiz)
[99] Kunakh O M, Lisovets O I, Yorkina N V and Zhukova Y O 2021 *Biosystems Diversity* **29**(3) 84–93 URL https://doi.org/10.15421/012135
[100] Apostolov L G 1981 *Pest entomofauna of the forest biocenosis of Central Dnieper* (Kyiv (in Russian): Vyshcha Shkola)
[101] Barsov V 2001 *Conservation work* **7**(1) 39–43
[102] Kunah O N, Prokopenko E V and Zhukov A V 2014 *Fundamental and Applied Soil Science* **15**(1–2) 101–119 URL https://doi.org/10.15421/041410
[103] Solonenko A M, Arabadzhy-Tipenko L I, Kunakh O M and Kovalenko D V 2020 *Biosystems Diversity* **28**(3) 216–223 URL https://doi.org/10.15421/012028
[104] Razumovsky O 2003 *Polignozis* **2**(22)
[105] Pakhomov O Y, Kunakh O M, Babchenko A V, Fedushko M P, Demchuk N I, Bezuhla L S and Tkachenko O S 2019 *Biosystems Diversity* **27**(4) 322–328 URL https://doi.org/10.15421/011942
[106] Zhukov O, Kunah O, Fedushko M, Babchenko A and Umerova A 2021 *Ekológia (Bratislava)* **40**(2) 178–188 URL https://doi.org/10.2478/eko-2021-0020
[107] Matveev N 2011 *The Basics of Steppe Forestry by professor A.L. Belgard and their modern interpretation* (Samara: Samara University)
[108] Budakova V S, Yorkina N V, Telyuk P M, Umerova A K, Kunakh O M and Zhukov O V 2021 *Biosystems Diversity* **29**(2) 78–87 URL https://doi.org/10.15421/012111
[109] Kunakh O M, Yorkina N V, Zhukov O V, Turovtseva N M, Bredikhina Y L and Logvina-Byk T A 2020 *Biosystems Diversity* **28**(1) 3–8 URL https://doi.org/10.15421/012001
[110] Nazarenko N N 2016 *Biosystems Diversity* **24**(1) 8–14 URL https://doi.org/10.15421/011602
[111] Zhukova Y O, Yorkina N V, Budakova V S and Kunakh O M 2020 *Biosystems Diversity* **28**(4) 390–398

URL https://doi.org/10.15421/012050
[112] Fedonenko E V, Kunakh O M, Chubchenko Y A and Zhukov O V 2022 *Biosystems Diversity* **30**(2) 179–190 URL https://doi.org/10.15421/012219
[113] Potapenko O, Kunah O M and Fedushko M P 2019 *Biosystems Diversity* **27**(1) 43–50 URL https://doi.org/10.15421/011907
[114] Kunakh O M, Yorkina N V, Turovtseva N M, Bredikhina J L, Balyuk J O and Golovnya A V 2021 *Ecologia Balkanica* **13**(2) 57–73
[115] Kunakh O, Zhukova Y, Yakovenko V and Daniuk O 2022 *Ekológia (Bratislava)* **41**(2) 113–125 URL https://doi.org/10.2478/eko-2022-0012

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Research on the application of on-board energy storage on an electric locomotive for quarry railway transport

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Abstract. Methods of using on-board energy storage system on rolling stock are considered. Their use ensures a reduction in energy consumption and reduces the impact on the environment. Concepts of managing energy flows in the traction system of an electric rolling stock equipped with onboard energy storage systems are considered. It is proposed to apply the concept of control on an electric locomotive for quarry railway transport, which consists in reducing the current consumption from the traction network during the acceleration of the rolling stock and compensating the power during movement with the lowest voltage on the current receiver. For the selected control concept, a simulation of the train movement on the test section was carried out while varying the value of the limit current consumed by the electric locomotive from the traction network. The power of the energy storage device and its working energy capacity is determined. Based on the results of the study, it is justified to limit the current consumed by the electric locomotive of the traction network at the level of 600 A.

1. Introduction

Increasing the efficiency of quarry railway transport is an important direction for achieving the goals of decarbonization and sustainable development of mining enterprises.

A well-known method of increasing the efficiency of electric traction systems is the use of recuperation [1]. For this, it is necessary to use energy storage systems in the electric traction system. For electric traction systems of quarry transport, it is expedient to use on-board energy storage systems (OESS), because, firstly, it allows the most effective use of recuperation energy, and secondly, it provides the possibility of autonomous movement of electric rolling stock in non-electrified sections.

The concept of managing energy flows in the electric traction system is important for the effective use of OESSs. The analysis of the sources shows that the structure and parameters of the traction electric drive and OESS depend on the type of rolling stock and its operating conditions [2].

Nowadays, several types of an electric rolling stock equipped with OESS are in operation.

The traction electric drive MITRAC Energy Saver [3] is designed for use in urban electric transport. OESS is built using supercapacitors. Discharge of the supercapacitor occurs when the tram accelerates. During electrodynamic braking and at a stop, the OESS is charged. The EV-E301 regional railcar train of Japan's JR East [4] operates on a route that has a non-electrified section. The strategy of control is as follows: when moving along an electrified section, the traction and auxiliary systems of the train are powered and the OESS is charged from the catenary network. When moving through a non-electrified section, the traction and auxiliary systems of the train are powered by the OESS. During electrodynamic braking, auxiliary systems are powered and OESS is charged. At the stop, auxiliary systems are powered and the OESS is charged from the contact network. Accumulators are used in OESS.

A feature of the Flexity 2 tram system developed by Bombardier for Nanjing [5] is that the contact network is available only near the stops. Therefore, the operating algorithm of the OESS is similar to that described above: when moving under the contact wire, the tram accelerates and the OESS is charged. Movement between stops is carried out with the power supply of the traction and auxiliary systems from the OESS. OESS is built using accumulators.

The tram system of the CAF development in Birmingham [6] functions similarly. The OESS of the rolling stock is built based on supercapacitors.

When the BEC-819 train, created by Hitachi [7] is moving in the traction mode, the traction and auxiliary systems are powered from the contact network through active rectifiers. There is no energy exchange with the OESS in this mode. When moving in coasting mode, charging of the OESS from the contact network begins. In the mode of electrodynamic braking, the OESS is charged. When moving along non-electrified areas, traction and auxiliary systems are powered by OESS.

The Combino Plus tram manufactured by Siemens [8] is equipped with a hybrid OESS, which includes batteries and supercapacitors. During acceleration, the tram systems are powered by supercapacitors. Power is supplied from the batteries in the driving mode with speed maintenance or coasting. During electrodynamic braking, supercapacitors are charged. At the stop, batteries and supercapacitors are recharged from the contact network.

Let's consider the algorithms of OESS operation on autonomous rolling stock.

A diesel train produced by Hitachi [9] uses battery-based OESS. OESS feeds the traction and auxiliary system during acceleration. After a speed of 30 km/h, a diesel generator connects, which provides energy to the diesel train system. During electrodynamic braking, OESS is charged. At a stop, auxiliary systems are powered from the OESS.

The tram produced by CRRC for Tangshan [10] is equipped with fuel cells and hybrid OESS. The fuel cell works with a certain power during the entire movement. When accelerated, the traction system is additionally powered by supercapacitors. In steady motion mode, if necessary, the traction system is powered by batteries. During electrodynamic braking, supercapacitors are charged. At the stop, OESS is recharged from fuel cells.

To ensure long-term autonomous movement of rolling stock on non-electrified sections, as well as in the case of a battery power source, OESS is built based on batteries of various types [11–15]. For the most part, this rolling stock is in trial operation, including checking and finalizing OESS management strategies.

It is worth noting that inertial energy accumulators were used on rolling stock [16, 17]. However, their exploitation was more of an experimental nature and they did not become widespread.

A generalization and analysis of energy exchange control concepts for electric traction systems can be found, for example, in [18–20]. Here we note that one of the methods of controlling the OESS consists in reducing the current consumption from the main power source during the acceleration of the rolling stock and ensuring optimal operating modes of the main power source. This OESS concept of control can be applied to an electric locomotive for quarry railway transport and is based on the following.

Observation of the operation of traction units at mining enterprises shows that the voltage on their current receivers can significantly decrease – down to a minimum voltage equal to 7.5 kV in the case of an alternating current electric traction system. Mostly, this happens when a loaded train is moving uphill. To prevent the minimum voltage protection from triggering, the control system or the driver limits the electric locomotive's current consumption from the traction network. As a result, the speed of the train decreases, and the passage time of the section increases.

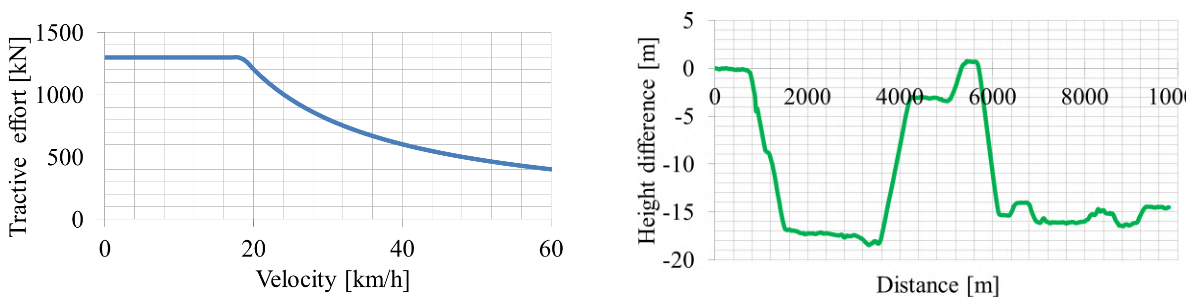
To eliminate the above situation, it is possible to use an OESS, which, in case of reaching a certain value of current that the electric locomotive consumes from the catenary network, will feed the traction electric drive and auxiliary systems. Thus, there is a problem with researching the processes of energy exchange in the traction system of an electric locomotive with an onboard OESS while limiting the current consumed from the contact network and determining the parameters of the OESS.

2. Research material and results

Direct modeling of the processes of energy consumption by an electric locomotive with an asynchronous traction electric drive during the movement of a train on a section of the track will not ensure high reliability of the results, since the traction network has a complex topology, its parameters cannot be determined with high accuracy, the nature of the movement of trains along the feeder zone is random. Therefore, let's assume that the movement of the electric locomotive under study in the section takes place at a voltage of 7.5 kV, that is, it is carried out at the minimum value of the voltage on the current receiver. Such a scenario corresponds to the worst conditions of the power supply of electric rolling stock.

The current consumed from the contact network is determined both by the mode of operation of the traction electric drive and by the power consumed by auxiliary systems. Let's assume that when a certain value of the current consumed by the electric locomotive from the contact network is exceeded, the OESS must be connected to power its systems. We will calculate the power and working capacity of the OESS at different limit values of the current that can be consumed from the network.

For example, let's study the electric locomotive described in [21]. Its traction characteristic is shown in figure 1a, and the profile of the section from the crushing plant to the reloading point is shown in figure 1b.



(a) (b)

Figure 1. Traction characteristics of the electric locomotive (a) and profile of the track section (b).

To solve the traction task, a mathematical model of train movement on a section of the track, given in [22], was used. With its help, the dependence of the tangential power was received for the case of the movement of a loaded train from the loading point to the crushing plant (figure 2).

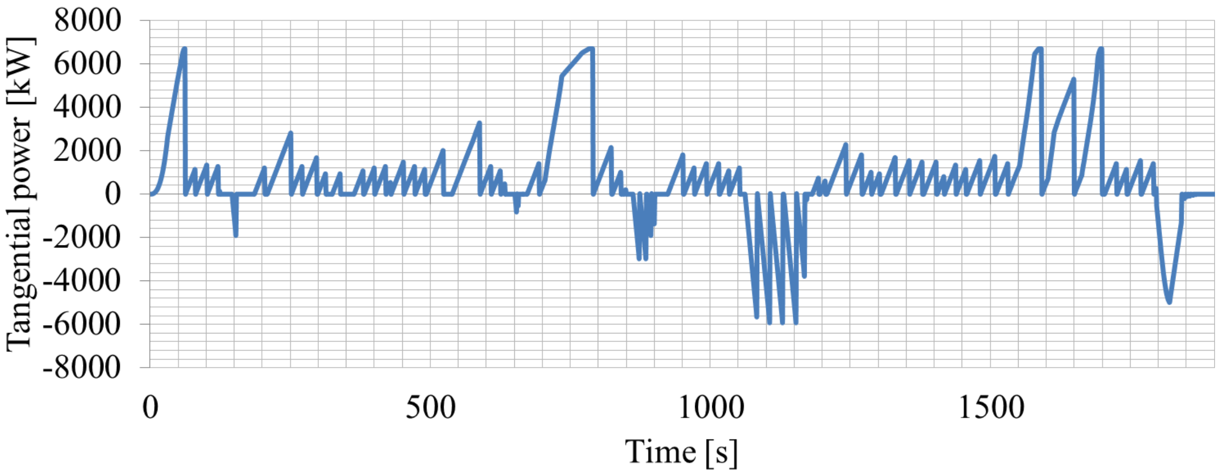


Figure 2. Dependence of the tangential power of the electric locomotive.

One of the variants of the structure of the traction system of the electric locomotive under study, in which power compensation from the OESS is ensured, is shown in figure 3. Here the intermediate circuit, to which the traction electric drive and auxiliary systems are connected, is fed jointly from the input converter and the OESS.

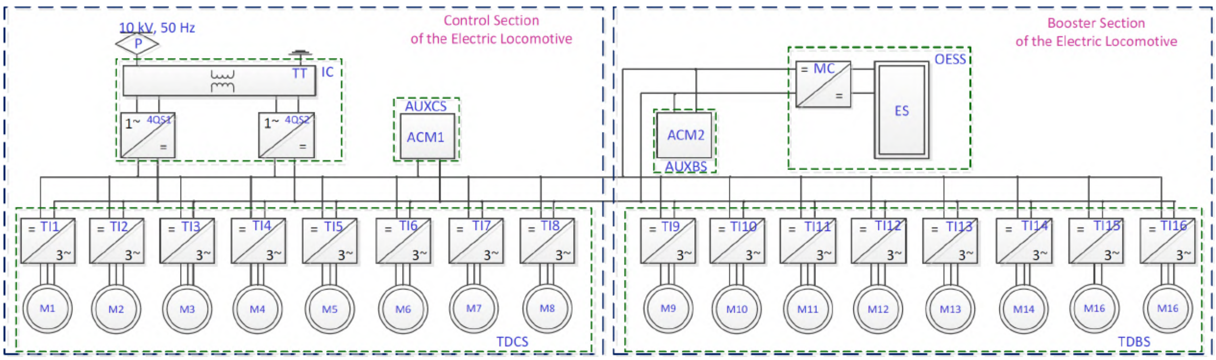
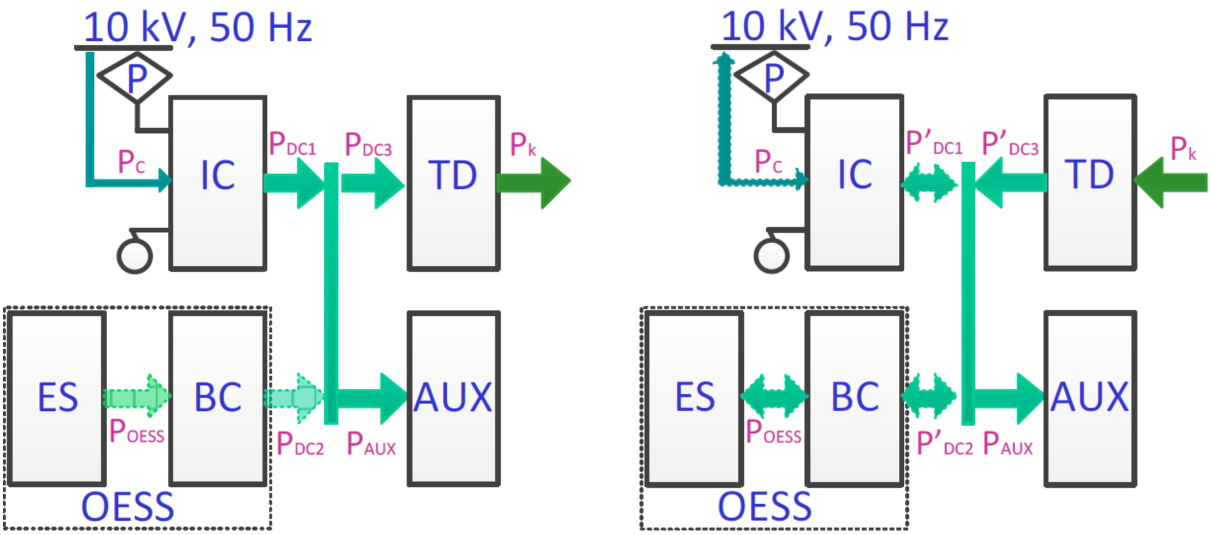


Figure 3. Structural diagram of the traction system of the electric locomotive: P – pantograph, IC – input converter, TT – traction transformer, 4QS1, 4QS2 – four-quadrant converters; AUXCS – auxiliary systems of electric locomotive control, ACM1 – auxiliary converter module of control section, ACM2 – auxiliary converter module of booster section, OESS – energy storage system, ES – energy storage, MC – matching converter, TDCS – traction electric drive of the control section, TDBS – traction electric drive of the booster section, TI1...TI16 – traction inverters, M1...M16 – traction induction electric motors.

The power flow management algorithms are as follows.

In traction mode (figure 4a), the power consumed from the traction network is determined through the active component. If the total load is a tangential power and auxiliary systems, exceed this power, then the OESS is connected to the power supply of the load.

In the electrodynamic braking mode (figure 4b), the energy coming from the traction electric drive can be used to power the auxiliary systems of the electric locomotive (priority use), charge the OESS, and recuperate into the traction network (in case there is an excess of the total power of the auxiliary systems and the power, with which the energy storage (ES) is charged). If there is not enough energy to power auxiliary systems, the rest is compensated from the traction network. If during braking, the power coming from the traction electric drive exceeds the total power of auxiliary systems and OESS, the excess energy is recovered to the traction network. At the same time, the latter is possible if there is an OESS power limit.



(*a*) (*b*)

Figure 4. Energy flows in the traction system of an electric locomotive is traction mode (*a*) and EBD mode (*b*): P – pantograph, IC – input converter, TD – traction electric drive, OESS – on-board energy storage system, ES – energy storage, BC – matching converter, AUX – auxiliary systems, PC – power that is consumed from the traction network, P_{DC1} – power that enters the intermediate circuit from the input converter, P_{DC2} – the power that comes from to the intermediate circuit from OESS, POESS – power that is consumed from ES, P_{DC3} – power that is transmitted to the traction electric drive, P_{DAUX} – power consumed by auxiliary systems, P_k – tangent power of the electric locomotive, P'_{DC3} – power that comes from the traction electric drive, P'_{DC2} – the power that is transferred to the OESS, P'_{DC1} – the power consumed from the traction network in EDB mode.

To perform the calculations by the above, energy flow management algorithms were developed, the block diagram of which is shown in figure 5. The diagram does not show the calculation of the energy that is recovered to the traction network.

As mentioned above, two scenarios of operation are possible in EDB mode.

In the first scenario, the capacity of ES is sufficient to store all available energy. In this case, the power must ES meet the condition

$$P_{OESS} \geq P_{Lnom}\eta_{TD}\eta_{DC} \tag{1}$$

where P_{Lnom} – nominal tangent power of the electric locomotive, η_{TD} – the efficiency of "traction converter – electric motor – reduction gear" is taken as equal to 0.9; η_{BC} – the efficiency of the matching converter of the OESS assuming to be equal to 0.9.

The second scenario foresees that the storage capacity is selected from the condition of power compensation in traction mode. The storage capacity in this case is calculated using

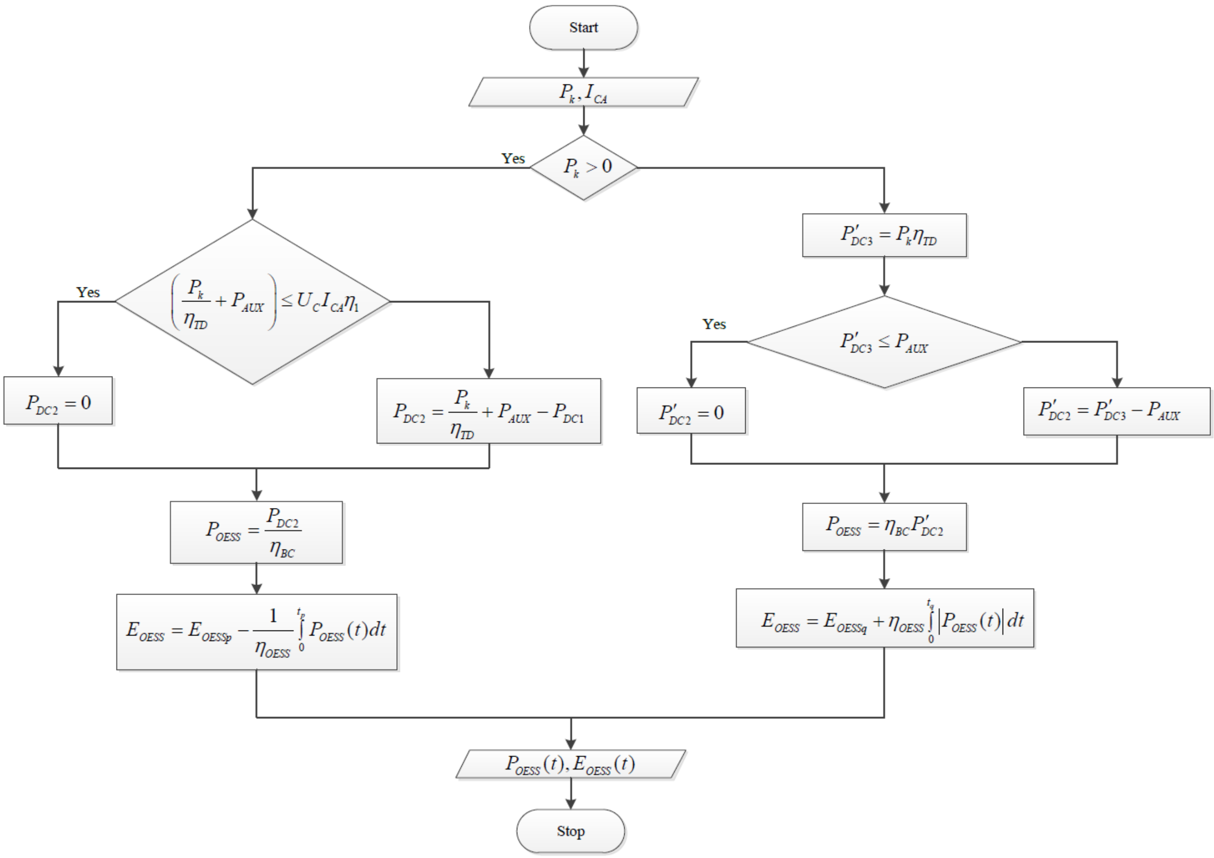


Figure 5. Block diagrams of the energy flow management algorithm in the traction system of the electric locomotive.

the expression

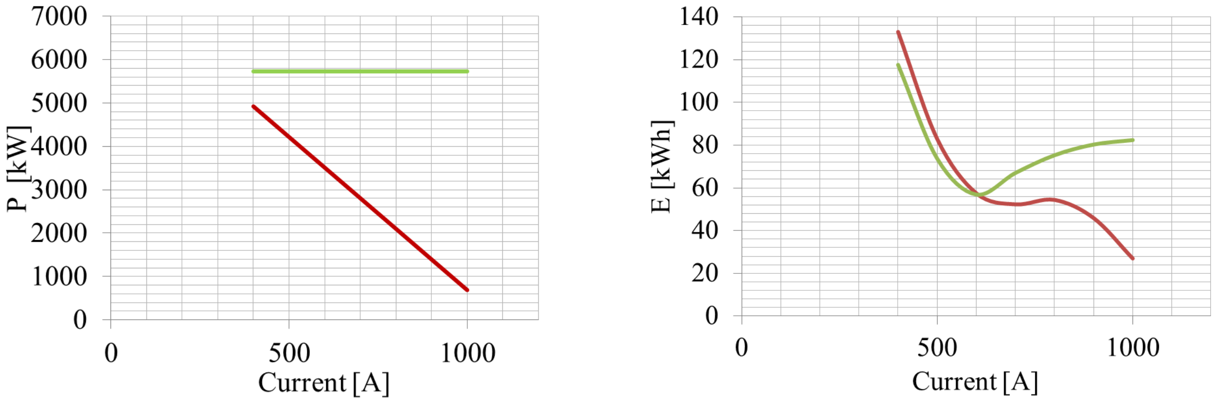
$$P_{OESS} \geq \frac{\frac{P_{Lnom}}{\eta_{TD}} + P_{AUX} - U_C I_{CA} \eta_1}{\eta_{BC}} \tag{2}$$

where η_1 – the efficiency of the "traction transformer – input converter – filter" link is taken as 0.95; P_{AUX} – the power of auxiliary systems of the electric locomotive is assumed to be equal to 300 kW, U_C – the lowest voltage on the current receiver, equal to 7.5 kV, I_{CA} – the limit current consumed by the electric locomotive from the traction network.

Figure 6 shows the dependence of the power of the ES (figure 6a) and the working energy capacity of the ES (figure 6b) on the limited current consumed by the electric locomotive. The calculations have been provided for the limit current range of 400...1000 A. The power of the ES and the working energy capacity were determined during the calculations. The corresponding dependencies are shown in figure 6.

The analysis of dependencies in figure 6 shows that in the first scenario – determination of the OESS power from the condition of complete energy absorption in the EBD mode – the ES power is a constant value. The working energy capacity in this case has a non-linear character with a minimum of about 600 A.

For the second scenario – determining the power of the energy storage device from the condition of power compensation while limiting the current consumption – the power is ES a linear dependence. The dependence of the working energy capacity is non-linear, and in the current range of 600...800 A it has a shade with an almost constant value.



(a) (b)

Figure 6. Dependencies of power (a) and and working energy capacity (b) of the energy storage (green line – scenario 1, red line – scenario 2).

It should be noted that the power values calculated according to (1) and (2) at a certain value of the limit current of the electric locomotive give the limits of the range in which the power can be ES. If the power is ES less than calculated by expression (2), then the power compensation mode will not be provided. If the ES power is greater than calculated according to (1), then there will be an irrational use of ES, since this value is the maximum ES power with which it can work in the case under study.

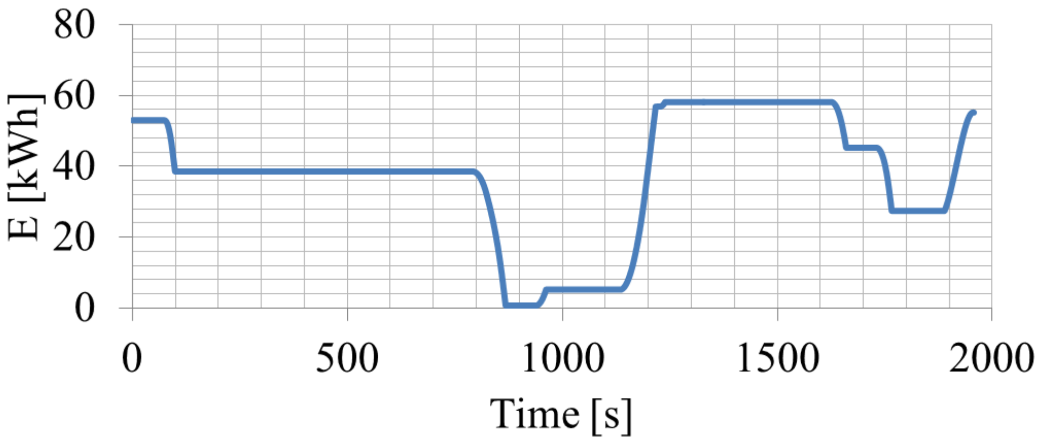
Thus, the determination of ES power and working energy capacity requires additional research. In general, both determining the parameters of the ES and determining the parameters of the entire traction system is a complex task [23–25].

Regarding the determination of the limit current of an electric locomotive, which can be consumed by an electric locomotive from the catenary network, the following must be taken into account.

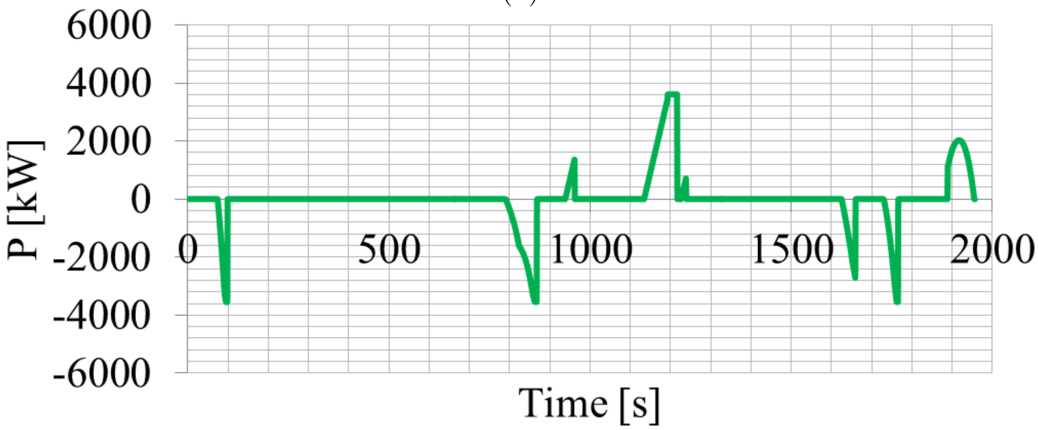
1. A system of copper contact wire and a bimetallic supporting cable is used in the contact suspension on the quarry railway transport. The continuous current of the PBSM-95+MF-100 contact network is 660...820 A depending on the degree of wear of the contact wire [26, 27], while an increase in current by 1.3 times is allowed if the duration of its flow does not exceed 3 minutes. Since the actual degree of wear of the contact wire is unknown, and, in addition, there may be several electric locomotives on one feeder zone, it is advisable to take the limiting current close to the lower limit of the range.
2. It is shown in [21] that when moving along the investigated section of the track, the movement of an electric locomotive with nominal power in the traction mode is carried out only uphill, and most of the time – 70.5% of the total time of movement in the traction mode – the traction drive operates with a power that does not exceed 1500 kW. The maximum value of the tangent power on flat areas is 3500 kW, which is 52.2% of the nominal power. That is, in speed maintenance modes, about 50% of the power of the electric locomotive is sufficient. Based on this, the current of the electric locomotive will be

$$I_1 = \frac{P_k}{U_1 \eta \cos\varphi} \tag{3}$$

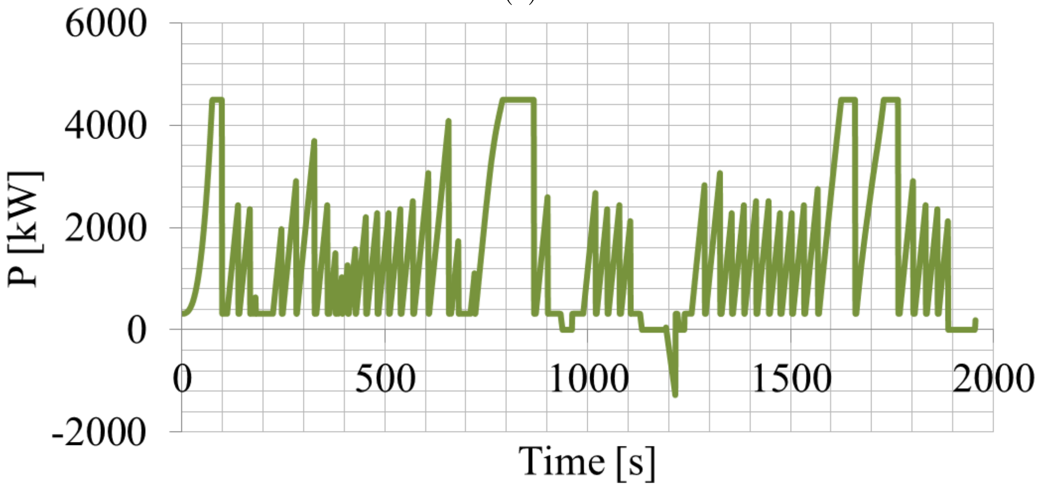
where P_k – tractive power, which is equal to 3500 kW; U_1 – the voltage on the current receiver, equal to 7.5 kV; η – efficiency factor of the electric locomotive, which can be taken



(a)



(b)



(c)

Figure 7. Dependencies of changes in energy (a), power (b) of the energy storage, and current consumed by the electric locomotive from the catenary network (c).

as equal to 0.86, $\cos\varphi$ – the power factor of the fundamental harmonic, which is assumed to be equal to 0.95.

After performing the calculations, we will get that the fundamental harmonic of the network current of the electric locomotive is about 570 A.

3. Decreasing the limit current of the electric locomotive leads to a reduction in the power – and therefore the cost – of the traction transformer of the input converter and the filters associated with it. However, it leads to an increase in the power and capacity of the OESS. Since the cost of electrical equipment is unknown, this aspect is not taken into account when determining the limiting current.

Thus, by comparing the first two aspects and the results of the calculation of the ES parameters, the limit current of the electric locomotive can be taken as equal to 600 A.

For example, figure 7 shows the dependencies of the change in the energy of the ES (a), its power (b), and the current consumed by the electric locomotive from the catenary network (c). The current limit is set to 600 A.

As can be seen from figure 7, when a current of 600 A is reached, the ES "switches on" to work. This happens during acceleration and movement on hills. In the EDB mode, when driving downhill, braking at the end of the movement, the energy enters the ES and even returns to the contact network. At the same time, the current that the electric locomotive consumes from the contact network does not exceed 600 A.

Thus, the algorithm described above can be used to determine the parameters of the onboard energy storage during working with current limitations. It is rational to simulate the movement of the train during the entire half-passage, as well as maneuvering during loading and unloading if during these operations the power is supplied from the onboard energy storage. To improve the accuracy of calculation results, it is necessary to improve mathematical models, in particular, to determine the losses in the traction electric drive.

3. Conclusions

The concepts of onboard energy storage management have been analyzed. Their use on rolling stock allows for storing of the energy during braking, which is later used during the movement of rolling stock.

For the electric locomotive of quarry railway transport, it is proposed to implement the mode of operation to limit the current consumed by the electric locomotive from the catenary network, and the energy exchange processes for this method of control have been investigated.

Calculations have been made and a justification has been provided for determining the limit current that can be consumed by an electric locomotive from the catenary network. Restriction of the limit current to 600 A is rational for the electric locomotive under study.

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References

[1] Sychenko V G, Kuznetsov V G, Bosiy D O and Sablin O I 2017 *Energy of traction networks* (Dnipro: Standard-Service)

[2] Fedele E, Iannuzzi D and Del Pizzo A 2021 *IET Electrical Systems in Transportation* **11**(4) 279–309 URL `https://doi.org/10.1049/els2.12026`

[3] Steiner M, Klohr M and Pagiela S 2007 Energy storage system with ultracaps on board of railway vehicles *2007 European Conference on Power Electronics and Applications* pp 1–10 URL https://doi.org/10.1109/EPE.2007.4417400
[4] Kono Y, Shiraki N, Yokoyama H and Furuta R 2014 Catenary and storage battery hybrid system for electric railcar series EV-E301 *2014 International Power Electronics Conference (IPEC-Hiroshima 2014 - ECCE ASIA)* pp 2120–2125 URL https://doi.org/10.1109/IPEC.2014.6869881
[5] Becker F and Dämmig A 2016 Catenary free operation of light rail vehicles – Topology and operational concept *2016 18th European Conference on Power Electronics and Applications (EPE'16 ECCE Europe)* pp 1–10 URL https://doi.org/10.1109/EPE.2016.7695286
[6] Reynaud J F, Garmendia M and Nieva T 2018 Comprehensive integration of Onboard Energy Storage systems in tramways: Birmingham tram case study *2018 IEEE International Conference on Electrical Systems for Aircraft, Railway, Ship Propulsion and Road Vehicles & International Transportation Electrification Conference (ESARS-ITEC)* pp 1–6 URL https://doi.org/10.1109/ESARS-ITEC.2018.8607554
[7] Ogasa M and Taguchi Y 2010 Development of contact-wire/battery hybrid LRV *2010 IEEE Vehicle Power and Propulsion Conference* pp 1–6 URL https://doi.org/10.1109/VPPC.2010.5728994
[8] Holland Innovation Network China 2019 Overview of Hydrogen and Fuel Cell Developments in China URL https://transitionaccelerator.ca/wp-content/uploads/2020/07/HollandInnovationNetworkinChina-Hydrogendevelopments.January2019-1.pdf
[9] Tokuyama K, Shimada M, Terasawa K and Kaneko T 2008 *Hitachi Review* **57**(1) 23–27 URL https://www.hitachi.com/rev/pdf/2008/r2008_01_003.pdf
[10] Chen W, Liu Z and Zhang X 2016 Fuel Cell Based Hybrid Power System Design For A Passenger Tram *WHEC 2016 - 21st World Hydrogen Energy Conference 2016* vol 51 pp 1119–1121 URL https://docplayer.net/26235450-Fuel-cell-based-hybrid-power-system-design-for-a-passenger-tram.html
[11] Wabtec Corporation 2023 FLXdrive URL https://www.wabteccorp.com/locomotive/alternative-fuel-locomotives/flxdrive
[12] Express Service 2023 Battery Locomotives URL https://lz1866.com/index.php?/battery-locomotives
[13] Stadler Rail AG 2022 FLIRT Akku URL https://www.stadlerrail.com/en/flirt-akku/details/
[14] Siemens 2021 Battery-powered Mireo Plus B decarbonises Europe's railways URL https://press.siemens.com/global/en/feature/battery-powered-mireo-plus-b-decarbonises-europes-railways
[15] Alstom 2021 Alstom presents its battery-powered multiple unit train in Saxony URL https://www.alstom.com/press-releases-news/2021/9/alstom-presents-its-battery-powered-multiple-unit-train-saxony
[16] Ogasa M 2010 *IEEJ Transactions on Electrical and Electronic Engineering* **5**(3) 304–311 URL https://doi.org/10.1002/tee.20534
[17] Lenhard D, Engel B, Langwost J and Söffker C 2008 *Elektrische Bahnen* **98**(1) 279–289
[18] Sydorenko A and Yatsko S 2022 *Transport systems and technologies* (39) 115–127 URL https://doi.org/10.32703/2617-9040-2022-39-11
[19] Khozia P and Sulym A 2021 *Transport systems and technologies* (38) 63–79 URL https://doi.org/10.32703/2617-9040-2021-38-63-6
[20] Buryakovskiy S, Maslii A, Pomazan D, Maslii A, Panchuk O and Rybin A 2020 Study of Methods for Charging of Energy Storage Devices of Railway Traction Units *2020 IEEE Problems of Automated Electrodrive. Theory and Practice (PAEP)* pp 1–5 URL https://doi.org/10.1109/PAEP49887.2020.9240794
[21] Riabov I, Mosin S, Overianova L, Kondratieva L, Demydov O and Goolak S 2022 *Transport systems and technologies* (39) 83–100 URL https://doi.org/10.32703/2617-9040-2022-39-9
[22] Riabov I, Liubarskyi B, Overianova L, Goolak S and Kondratieva L 2022 Mathematical model of the electric traction system of quarry railway transport *Proceedings of 26th International Scientific Conference. Transport Means 2022* pp 330–335
[23] Lyubarsky B H 2014 *Theoretical basis for the selection and evaluation of prospective systems of electromechanical energy conversion of electric rolling stock* Dissertation ... Doct. Tech. Sciences: 05.22.09. – Electrotransport
[24] Goolak S, Kondratieva L, Riabov I, Lukoševičius V, Keršys A and Makaras R 2023 *Energies* **16**(7) 3293 URL https://doi.org/10.3390/en16073293
[25] Kletska O, Falendysh A, Ivanchenko D, Dizo J and Kravchenko K 2021 *E3S Web of Conferences* **280** 06001 URL https://doi.org/10.1051/e3sconf/202128006001
[26] Dryzhenko A Y 2014 *Open-pit mining works* (Dnipropetrovsk: NSU)
[27] Kondratieva L, Bogdanovs A, Overianova L, Riabov I and Goolak S 2023 *Archives of Transport* **65**(1) 119–135 URL https://doi.org/10.5604/01.3001.0016.2631

The economic potential of enhanced method of anaerobic fermentation with green ammonia production for European energy market

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The economic potential of enhanced method of anaerobic fermentation with green ammonia production for European energy market

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Abstract. This scientific paper provides an analysis of the current state of biogas production and potential for improvement through optimizing biogas production and diversifying production. The analysis uses data from open sources and reports, such as EBA's Statistical Report and analytical reports on market and digestate analysis. The authors present a comparison of electricity costs and biogas plant distribution in Europe, confirming that the higher the cost of electricity, the more widespread the introduction of biogas plants as an alternative energy source. The paper also discusses the potential of green ammonia production during anaerobic digestion, which can increase the efficiency and sustainability of biogas production technologies. The innovative technology of ammonia production from livestock waste during anaerobic treatment reduces the amount of water needed for dilution and transforms dissolved ammonia, which is toxic for anaerobic fermentation, into a useful final product. The paper highlights the potential for economically attractive approaches that use existing infrastructure and can contribute to energy independence and sustainability. The authors conclude that optimization in terms of more optimal process conditions and diversification of production approaches can increase the sustainability of biogas production technologies and ensure broader use.

1. Introduction

The decrease in carbon dioxide emissions and adherence to green energy production has been in focus of European community for decades [1]. That adherence is declared in sustainable development programs by the EU and worldwide. For example, the strategies Europe 2020 [2], Europe 2030 [3], and The Long-term Strategy of the United States [4] declared the EU's and US's goals for CO2 emissions decreasing. However, the recent actions of the European Union related to Russian invasion of Ukraine has added a new focus on urgent solving of energy issues and development of new approaches of energy production.

Therefore, it is relevant to provide evaluation of the economic potential of the new energy production methods. Ammonia is an energy source that has recently received much attention due to its advantages, including decreed emission. However, using it as an energy source nowadays is irrelevant due to high production costs. However, recently, a new carbon-free method of ammonia production has been proposed [5] that may be more efficient compared to the traditional process of ammonia production.

2. Materials and methods

The current state of biogas production is analyzed using reports and data of open sources. The estimation of the amount of biogas in Europe was taken from EBA's Statistical Report [6, 7]. The location of the biogas plants in Ukraine was collected and aggregated in online Google Map layer. The potential of the ammonia and market analysis was calculated based on the USA's and the EU's statistical data. Market analysis of the digestate was taken from the analytical report [8] and evaluated through calculations based on the statistical data on farm animals.

3. Results and discussion

3.1. Current state of biogas production from organic waste in Ukraine and in the EU

Current energy crisis creates the conditions that needs the development of the energy production systems solving urgent current needs and that are sustainable in long-term. And economic efficiency is one of the most significant factors driving the development of specific technologies. This statement is confirmed by comparing data on electricity cost and biogas plants' distribution. There is a correlation that the higher the cost of electricity, the more widespread the introduction of biogas plants as an alternative energy source. Thus, the most developed biogas production has place in Germany and Italy, where the cost of electricity is the highest among EU countries, 140 and 135 €/MW [9], respectively (figure 1). It is also important to note that a significant part of the structure of electricity prices in these countries is a tax (that is, the price of energy purchase is artificially increased to fill countries' budgets and prioritize energy efficiency). Accordingly, if the activity is profitable, the entrepreneur will carry out such activity. The crisis requires precisely these conditions of dependence on the energy resources of the Russian Federation and the food crisis caused by the war in Ukraine. It seems relevant to provide approaches that are economically attractive and use existing infrastructure.

The development of anaerobic technologies in Europe is spread unevenly (figure 2). In some countries, there is an oversaturation of the market with biogas plants, in particular, focused exclusively on the production of energy, which can be unsustainable [10]. At the same time, there are countries where anaerobic fermentation is not widespread, and there is significant

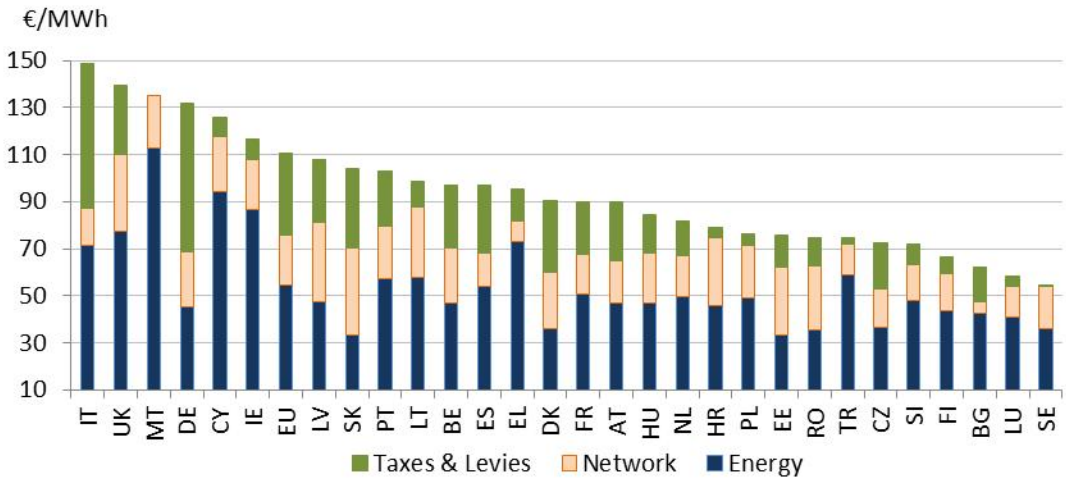

Figure 1. Average industry retail electricity prices in 2015 [9].

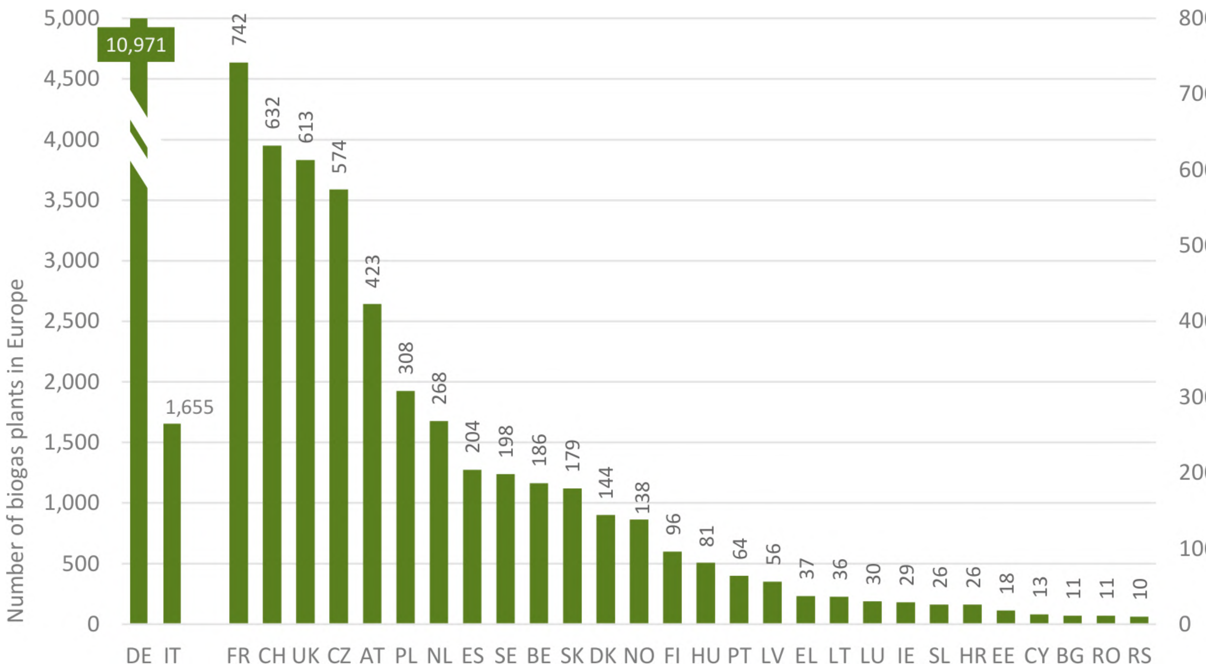

Figure 2. Number of biogas plants in European countries, arranged in descending order [6].

potential for its introduction. Thus, more than 11,000 biogas plants are operating in Germany and more than 1,600 in Italy. However, for example, in Romania and Bulgaria, the number of such plants is about 10 units per country, despite the relatively large territories of these countries.

In general, as of 2018, more than 50 facilities were producing biogas operated in Ukraine, of which 33 used organic waste. The total capacity of biogas plants was 44 MW. It is planned to build several biogas plants, particularly under the Ukrainian companies MHP and Danosha. The location of biogas facilities in different regions of Ukraine is presented in (figure 3).

3.2. Increasing economic efficiency of anaerobic fermentation for energy production

3.2.1. The potential of production of green ammonia during anaerobic digestion. Increasing economic efficiency by optimizing biogas production and diversifying production is the requirement for the anaerobic treatment technology to ensure energy independence of states. Both of these approaches will increase the sustainability of the approach and ensure the broader use of biogas production technologies [10]. Optimization in terms of more optimal process conditions is carried out quite widely and is inherent in many studies [11–13]. Here we will discuss the use of biofertilizers obtained in the process of anaerobic fermentation and the production of ammonia during the anaerobic fermentation of waste with a high nitrogen content.

Modern approaches make it possible to obtain additional products from organic waste when using anaerobic fermentation and ensure an increase in the efficiency of the process. The problem of accumulating a significant amount of ammonia in the anaerobic fermentation process, which leads to inhibition, has been known for a long time [14]. In order to reduce the inhibitory effect, there is a need to dilute the waste with water in an amount that could reach up to 12 times compared to the original substrate, which leads to additional costs and environmental impact. Using a sustainable technology of biogas production from livestock waste, it is possible to obtain such ammonia as a pure product, which can later be used as a fuel on a par with green hydrogen. The essence of the innovative ammonia production technology is the absorption of

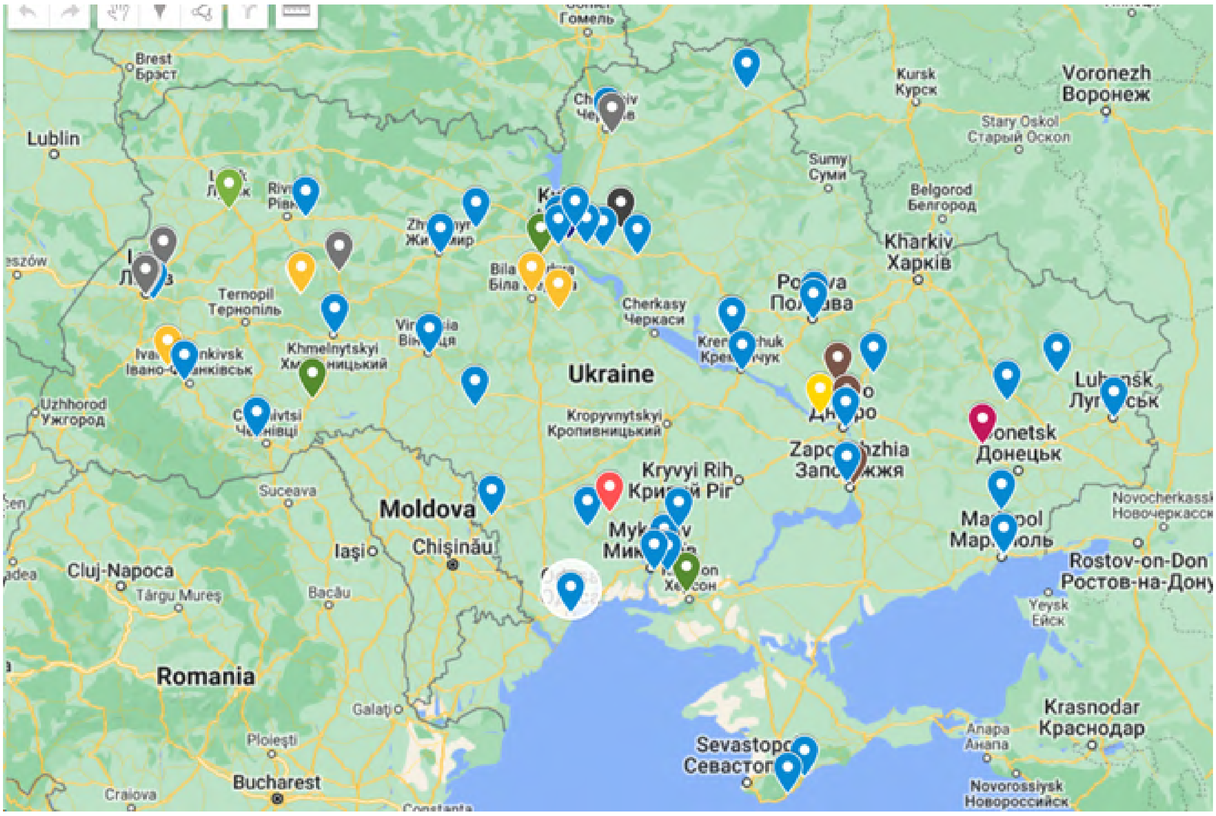

Figure 3. Location of facilities producing biogas in Ukraine.

ammonia during destruction in the process of anaerobic fermentation by the sorbent placed in the reactor and its subsequent regeneration (figure 4) [5]. Therefore, this approach reduces the amount of water needed for dilution and ensures the transformation of this dissolved ammonian which is toxic for anaerobic fermentation, into a final helpful product.

It is important to note that such technologies have high potential because, for example, the technology can, for the first time, ensure the production of ammonia cheaper than when using the Haber-Bosch process. In addition to anaerobic fermentation, there were other methods of obtaining ammonia from livestock waste, for example, using Escherichia coli [15] or using a hydrothermal approach [16]. However, they probably use not fewer resources than the traditional ammonia production approach.

The European Commission currently encourages the use and various production methods of green ammonia. Thus, there are projects funded by the European Commission on the electrochemical production of ammonia [17] and the use of ammonia in fuel cells for marine vessels [18].

The global market for green ammonium is 17 million dollars [19]. However, such relatively small market indicators are related precisely to the fact that there was no technology on the market that would be cheaper than the production of ammonia by the traditional method. It is predicted that the cost of green ammonia will gradually decrease, mainly due to the discovery of methods that make production cheaper and the introduction of ammonia production approaches in the industry. Thus, the price over 30 years may drop several times from the estimated average cost of 1,000 $ per ton to 500 $ per ton, potentially making it cost-competitive with ammonia obtained by traditional technology [20]. Figure 5 shows the forecast for the cost of ammonia until 2050.

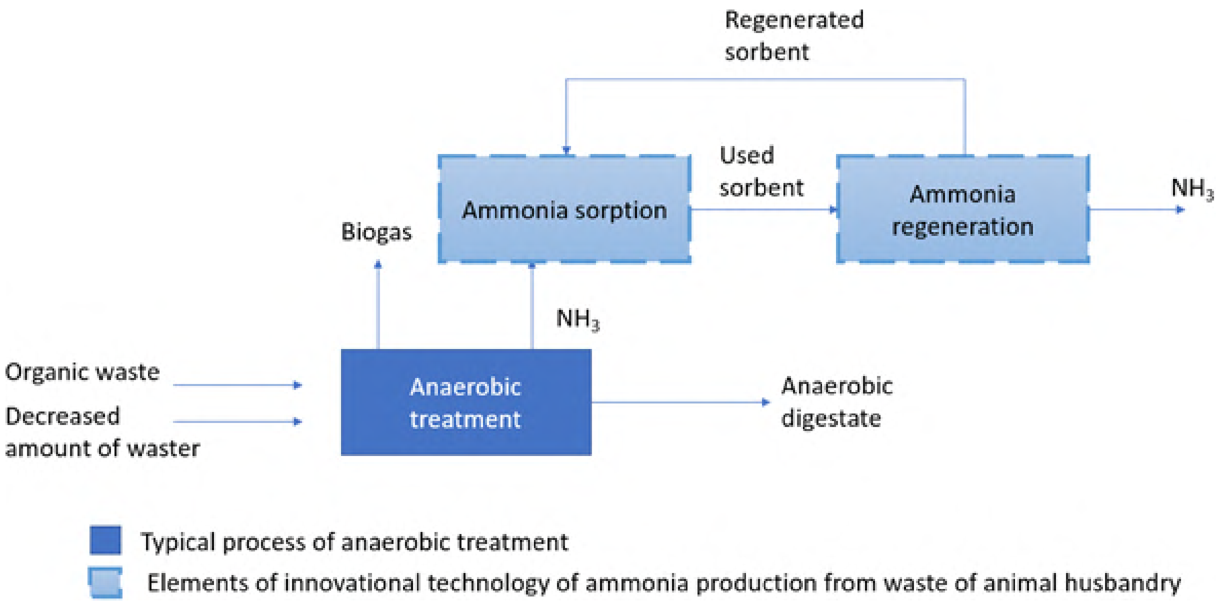

Figure 4. An innovative method of producing ammonia from livestock waste during anaerobic treatment [5].

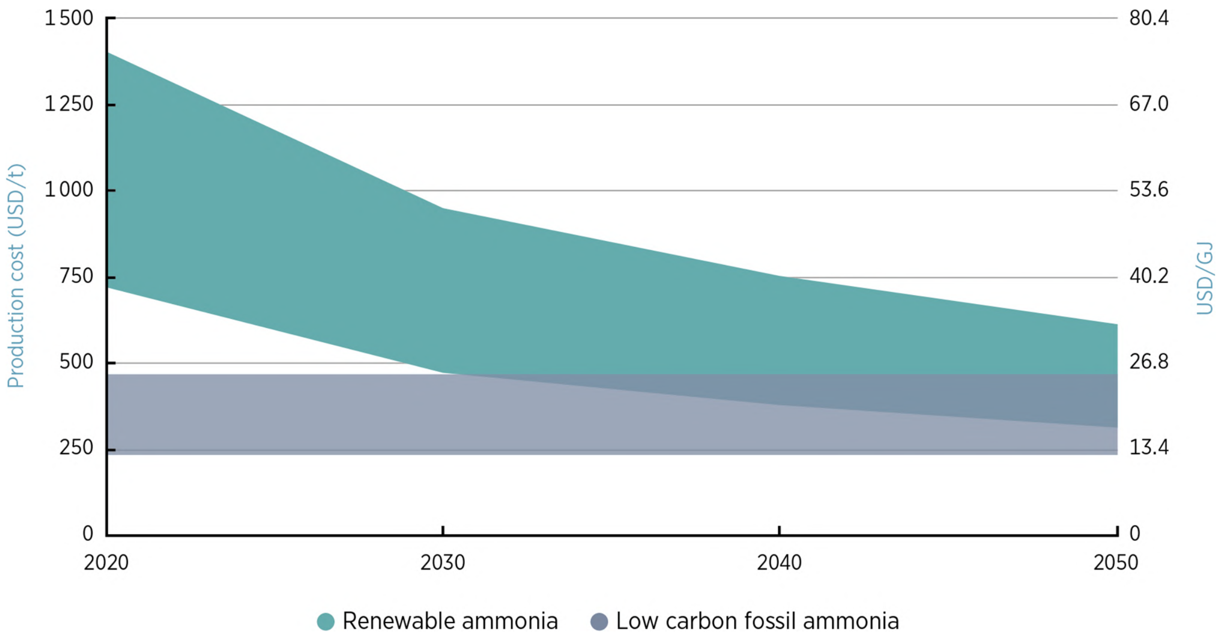

Figure 5. Ammonia cost forecast until 2050 [20].

In Europe, the potential of ammonia production from livestock waste by anaerobic fermentation reaches 10 million tons per year [21]. Ammonia production potential in the USA is commensurate with European ones (figure 6).

It is important to note that today the production of energy from ammonia produced by the Haber-Bosch process is considered unprofitable. So, the amount of energy required to produce a ton of ammonia by the Haber-Bosch method is 38 GJ. At the same time, 22.5 GJ of energy can be obtained from one ton of ammonia [22].

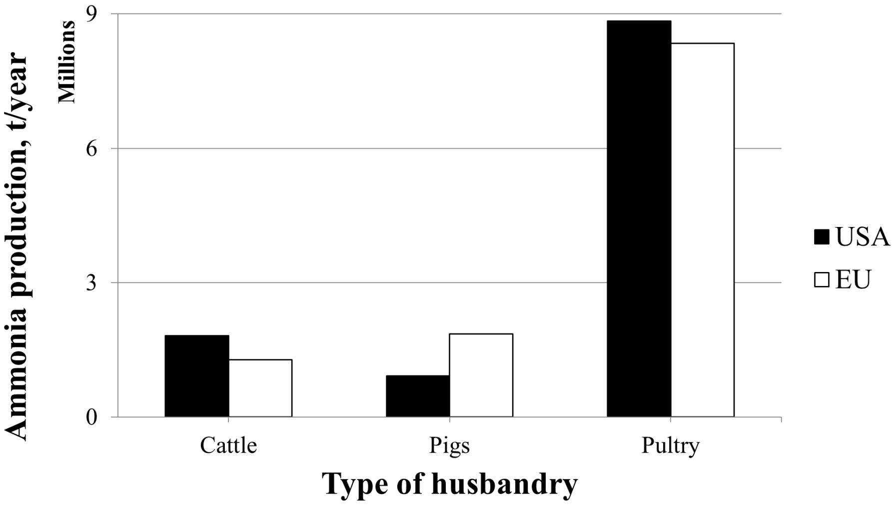

Figure 6. The potential of ammonia production using anaerobic fermentation technology from livestock waste in the USA and the EU [5].

In Ukraine, this method's potential for ammonia production can reach up to 0.1 million tons per year. Vinnytsia, Cherkasy, and Kyiv regions have the most potential for ammonia production due to the location of many livestock complexes.

Considering that the cost of ammonia is about 1,135 dollars per ton [21], the potential market for ammonia produced in this way can be about 11 billion dollars for Europe and the USA and about 0.11 billion dollars per year for Ukraine.

3.2.2. The potential of anaerobic digestate production. The anaerobic fermenters biofertilizers market is estimated at 45 Bn $ as of 2019, with a compound annual growth rate (CAGR) of 7.8% and a growth potential of over 75 Bn $ in 2026 (figure 7) [8].

However, the indicated figures look incomplete, as both the European Union and Ukraine have additional potential for the production of biofertilizers. The cost of the solid fraction of biofertilizers is 122 $ per ton [22], which is significantly cheaper than other types of fertilizers. The generated waste is 5,913,382 tons and 234,547 tons per day in Europe and Ukraine, respectively. Therefore, the market of biofertilizers can potentially reach about 263.3 and about 10.4 Bn $ per year in the EU and Ukraine, respectively. It is worth noting that the provided calculations were carried out using a rough methodology, assuming that all waste was sold as a solid fraction without considering mass changes in waste during fermentation. The calculation of the potential of the biofertilizer market in Europe and Ukraine is presented in table 1 and table 2. Data calculated considering that one animal of poultry, pigs, cows produces 0.16, 5.10, 55.00, kg of waste per day, respectively [23].

Also, the efficiency of the process may be enhanced by using addition technologies such as waste catalysis [26, 27], the use of nanoparticles [28–35] to provide additional purification. In addition optimization could be reached by using modern decision-making tools such as ontologies [36–39].

4. Conclusions

In conclusion, ammonia production by anaerobic fermentation of livestock waste has a high potential for Ukraine and the European Union. It is one of the promising ways to Ukraine's role in ensuring Europe's energy security, especially considering that the existing infrastructure of pipelines does not require significant modernization for the transportation of ammonia.

Figure 7. The economic potential of the biofertilizer market in the European market [8].

Table 1. Market potential of biofertilizers in the European Union.

Animal waste type	Number of animals, thousands of heads [24]	Waste production, t/day	Biofertilizer market potential, Bn \$ per year
Poultry	1570000	251200	11.19
Pigs	150320	766632	34.14
Cattle	89010	4895550	218.00
Cows	1809330	5913382	263.32

Table 2. Market potential of biofertilizers in Ukraine.

Animal waste type	Number of animals, thousands of heads [25]	Waste production, t/day	Biofertilizer market potential, Bn \$ per year
Poultry	251200	35278	1.57
Pigs	766632	29210	1.30
Cattle	3092	170060	7.57
Cows	229305	234547	10.44

Implementation of the modern approaches that correlate with sustainable development goals and the concept of circular economy may be an effective approach to solving European energetic challenges caused by Russian invasion of Ukraine.

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References

[1] Chen L, Msigwa G, Yang M, Osman A I, Fawzy S, Rooney D W and Yap P S 2022 *Environmental Chemistry Letters* **20**(4) 2277–2310 ISSN 1610-3661 URL https://doi.org/10.1007/s10311-022-01435-8
[2] 2010 COM(2010) 2020 final, Europe 2020: A strategy for smart, sustainable and inclusive growth URL https://www.eea.europa.eu/policy-documents/com-2010-2020-europe-2020
[3] 2019 Reflection Paper 'Towards a Sustainable Europe by 2030' URL https://www.eesc.europa.eu/en/our-work/opinions-information-reports/opinions/reflection-paper-towards-sustainable-europe-2030
[4] 2021 *The Long-Term Strategy of the United States: Pathways to Net-Zero Greenhouse Gas Emissions by 2050* (Washington DC: United States Department of State and the United States Executive Office of the President) URL https://www.whitehouse.gov/wp-content/uploads/2021/10/US-Long-Term-Strategy.pdf
[5] Zhadan S, Shapovalov Y, Tarasenko R and Salyuk A 2021 *Eastern-European Journal of Enterprise Technologies* **5**(8 (113)) 66–75 URL https://doi.org/10.15587/1729-4061.2021.243068
[6] 2019 EBA Statistical Report 2018: Annual Statistical Report of the European Biogas Association. Abriged Version Tech. rep. European Biogas Association Brussels URL https://www.europeanbiogas.eu/wp-content/uploads/2019/11/EBA_report2018_abriged_A4_vers12_220519_RZweb.pdf
[7] European Biogas Association 2016 Annual Report 2015 URL https://issuu.com/europeanbiogasassociation/docs/eba_annual_report_2015
[8] 2020 Europe Anaerobic Digestion Market Size By Feedstock (Organic Waste, Sewage Sludge, Energy Crops, Others), By Application (Residential, Commercial, Industrial), By Process (Wet AD, Dry AD), Industry Analysis Report, Country Outlook, Application Potential, Price Trend, Competitive Market Share & Forecast, 2020 – 2026 Tech. Rep. GMI2067 URL https://www.gminsights.com/industry-analysis/europe-anaerobic-digestion-market
[9] European Commission, Directorate-General for Energy 2016 REPORT FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS: Energy prices and costs in Europe URL https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52016DC0769
[10] Shapovalov Y B, Usenko S A, Salyuk A I, Tarasenko R A and Shapovalov V B 2022 *IOP Conference Series: Earth and Environmental Science* **1049**(1) 012023 URL https://doi.org/10.1088/1755-1315/1049/1/012023
[11] Ivanov V, Stabnikov V, Stabnikova O, Salyuk A, Shapovalov E, Ahmed Z and Tay J H 2019 *AIMS Materials Science* **6**(5) 821–832 ISSN 2372-0484 URL https://doi.org/10.3934/matersci.2019.5.821
[12] Abouelenien F, Nakashimada Y and Nishio N 2009 *Journal of Bioscience and Bioengineering* **107**(3) 293–295 ISSN 1389-1723 URL https://doi.org/10.1016/j.jbiosc.2008.10.009
[13] Šinkora M and Havlíček M 2011 *Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis* **59**(6) 343–354 ISSN 12118516 URL https://doi.org/10.11118/actaun201159060343
[14] Yenigün O and Demirel B 2013 *Process Biochemistry* **48**(5-6) 901–911 ISSN 1359-5113 URL https://doi.org/10.1016/j.procbio.2013.04.012
[15] Mikami Y, Yoneda H, Tatsukami Y, Aoki W and Ueda M 2017 *AMB Express* **7**(1) 83 ISSN 21910855 URL https://doi.org/10.1186/s13568-017-0385-2
[16] Matsumura Y, Suganuma Y, Ichikawa T, Kim W, Nakashimada Y and Nishida K 2021 *ACS Omega* **6**(36) 23442–23446 doi: 10.1021/acsomega.1c03418 URL https://doi.org/10.1021/acsomega.1c03418
[17] 2022 TOWARD EFFICIENT ELECTROCHEMICAL GREEN AMMONIA CYCLE | TELEGRAM | Project | Fact sheet | H2020 | CORDIS | European Commission URL https://www.doi.org/10.3030/101006941
[18] 2023 Piloting Multi MW Ammonia Ship Fuel Cells | ShipFC | Project | Fact sheet | H2020 | CORDIS | European Commission URL https://cordis.europa.eu/project/id/875156
[19] 2023 Green Ammonia Market Recent Developments & Emerging Trends URL https://www.marketsandmarkets.com/Market-Reports/green-ammonia-market-118396942.html
[20] Gielen D, Boshell F, Castellanos G, Rouwenhorst K and Brown T 2022 Renewable Ammonia's role in reducing dependence on Gas URL https://energypost.eu/renewable-ammonias-role-in-reducing-dependence-on-gas/
[21] Schnitkey G, Paulson N, Swanson K and Zulauf C 2021 *farmdoc daily* (11) 147 URL https://farmdocdaily.

illinois.edu/2021/10/management-decisions-relative-to-high-nitrogen-fertilizer-prices.html

[22] Vasco-Correa J, Manandhar A and Shah A 2018 Economic implications of anaerobic digestion for bioenergy production and waste management URL https://ohioline.osu.edu/factsheet/fabe-6611

[23] Vedenev A G and Vedeneva T A 2006 *Biogazovye tehnologii v Kyrgyzskoj Respublike [Biogas technologies in the Kyrgyz Republic]* (Belorus: Typography "Euro") ISBN 9967235268

[24] 2020 Livestock population in numbers URL https://ec.europa.eu/eurostat/web/products-eurostat-news/-/ddn-20200923-1

[25] State Statistics Service of Ukraine 2020 *Animal production of Ukraine 2019 [Tvarynnytstvo Ukrainy 2019]* (Kyiv) URL https://ukrstat.gov.ua/druk/publicat/kat_u/2020/zb/05/zb_tvaryny_2019.pdf

[26] Allen D 1992 The Role of Catalysis in Industrial Waste Reduction *Industrial Environmental Chemistry: Waste Minimization in Industrial Processes and Remediation of Hazardous Waste* ed Sawyer D T and Martell A E (Boston, MA: Springer US) pp 89–98 ISBN 978-1-4899-2320-2 URL https://doi.org/10.1007/978-1-4899-2320-2_8

[27] Jie X, Li W, Slocombe D, Gao Y, Banerjee I, Gonzalez-Cortes S, Yao B, AlMegren H, Alshihri S, Dilworth J, Thomas J, Xiao T and Edwards P 2020 *Nature Catalysis* **3**(11) 902–912 ISSN 2520-1158 URL https://doi.org/10.1038/s41929-020-00518-5

[28] Bondarenko M V, Khalyavka T A, Melnyk A K, Camyshan S V and Panasuk Y V 2018 *Journal of Nano- and Electronic Physics* **10**(6) 06039–1 – 06039–4 ISSN 23064277 URL https://doi.org/10.21272/jnep.10(6).06039

[29] Shymanovska V V, Bezrodna T V, Melnyk V I, Manzhara V S, Khalyavka T A, Viktorova T I and Baran J 2004 Spectral properties of different phase composition TiO2 *XVI International Conference on Spectroscopy of Molecules and Crystals* vol 5507 ed Puchkovska G O, Gavrilko T A and Lizengevich O I International Society for Optics and Photonics (SPIE) pp 53 – 61 URL https://doi.org/10.1117/12.569619

[30] Khalyavka T A, Tsyba N N, Kamyshan S V and Kapinus E I 2015 *Russian Journal of Physical Chemistry A* **89**(1) 148–151 ISSN 1531-863X URL https://doi.org/10.1134/S0036024415010124

[31] Kapinus E I, Viktorova T I and Khalyavka T A 2009 *Theoretical and Experimental Chemistry* **45**(2) 114–117 ISSN 1573-935X URL https://doi.org/10.1007/s11237-009-9071-z

[32] Khalyavka T A, Kapinus E I, Viktorova T I and Tsyba N N 2009 *Theoretical and Experimental Chemistry* **45**(4) 234–238 ISSN 1573-935X URL https://doi.org/10.1007/s11237-009-9087-4

[33] Bondarenko M V, Khalyavka T A, Petrik I S and Camyshan S V 2018 *Theoretical and Experimental Chemistry* **54**(1) 40–45 ISSN 1573-935X URL https://doi.org/10.1007/s11237-018-9543-0

[34] Shapovalova M V, Khalyavka T A, Shcherban N D, Khyzhun O Y, Permyakov V V and Shcherbakov S N 2020 *Nanosistemi, Nanomateriali, Nanotehnologii* **18**(3) 681–695 ISSN 18165230 URL https://doi.org/10.15407/nnn.18.03.681

[35] Bondarenko M V, Khaliavka T O, Shcherban N D and Tsyba M M 2017 *Nanosistemi, Nanomateriali, Nanotehnologii* **15**(1) 99–112 URL https://doi.org/10.15407/nnn.15.01.0099

[36] Dovgyi S and Stryzhak O 2021 Transdisciplinary Fundamentals of Information-Analytical Activity *Advances in Information and Communication Technology and Systems* ed Ilchenko M, Uryvsky L and Globa L (Cham: Springer International Publishing) pp 99–126 ISBN 978-3-030-58359-0 URL https://doi.org/10.1007/978-3-030-58359-0_7

[37] Shapovalov Y, Tarasenko R, Usenko S, Shapovalov V, Andruszkiewicz F and Dołhańczuk-Śródka A 2021 *Desalination and Water Treatment* **236** 226–239 URL https://doi.org/10.5004/dwt.2021.27689

[38] Shapovalov Y, Shapovalov V, Tarasenko R, Bilyk Z, Shapovalova I, Paschke A and Andruszkiewicz F 2022 *Educational Technology Quarterly* **2022**(3) 216–231 URL https://doi.org/10.55056/etq.40

[39] Stryzhak O, Horborukov V, Prychodniuk V, Franchuk O and Chepkov R 2021 *Journal of Physics: Conference Series* **1828** 012007 URL https://doi.org/10.1088/1742-6596/1828/1/012007

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Some features of the systems for monitoring and diagnostic hydro units technical condition with considering smart grid technology

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Some features of the systems for monitoring and diagnostic hydro units technical condition with considering smart grid technology

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Abstract. Recently, hydro units are used in maneuverable modes, which leads to an increase in the load on all elements of hydro units. It can lead to unpredictable failure of their components and even failures in the operation of the hydroelectric power plant. Therefore, the use of diagnostic systems is appropriate for solving such problems. The most promising non-destructive diagnostic systems are vibration diagnosis systems. However, the effectiveness of their use depends on the diagnosis algorithms, which depend on the features and functioning of the diagnosed unit of the power unit. In this work, some models of vibration signals of hydraulic units and features of the construction of vibration diagnostics systems of hydrogenerator units are considered

1. Introduction

Using the machine in maneuverable modes, which modes can lead to premature or unpredictable failure of their components and even to failures in the operation of the hydroelectric power plant. The ISO 19283:2020 standard [1] provides a comprehensive standardized description of test procedures that allow for a comprehensive approach to the diagnosis of the condition of hydraulic units based on the monitoring and diagnosis of the structural elements of the of the structural elements of the hydroelectric power plant. The requirements for automated monitoring and diagnostic systems are defined in the ISO 61850-7-410 standard [2] and other standards [3–7]. In addition, when building a system for monitoring and diagnosing hydro generators, it is necessary to take into account that a significant number of hydro generators are low-speed machines with a low frequency of rotation of the hydro generator up to 150 rpm. Such features of the machine should be taken into account when choosing a diagnostic method. A significant part of the problems related to control and diagnostics of power equipment can be considered as problems of pattern recognition in the diagnostic space. However, on the other side of the problems that arise during an operation and repair of power equipment, the methodologies used during the implementation of smart control and diagnostic systems should be divided into two separate groups:

- detection of a change in the technical condition caused by defects at an early stage of their development, when damages have not yet appeared in a clear form;
- search for defects based on their already identified signs.

Based on the assessment and with the knowledge of probable processes, it is possible to carry out remaining useful life prediction of the equipment and plan possible maintenance actions based on the actual technical condition of the equipment. The application of forecasts in practice allows flexible changes to be made to plans for reorganizing the use of generating power plant equipment to cover demand both on the electricity market and to meet one's own needs.

2. The structure of power equipment maintenance system

The main prerequisite for forecasting the remaining useful life prediction of hydro unit is the availability of information about the technical condition of the equipment or its components [8,9]. To obtain primary information, modern monitoring and diagnostic systems are equipped with smart sensors [10, 11]. Smart sensors provide the possibility of self-monitoring, which ensures obtaining data without abnormal values, which can be used without preprocessing to determine the state of the equipment or its units.

The obtained data are intended for use as input data for analysis systems of means of diagnosing the technical state of the component. The technical condition of the component depends on the actual conditions in which the generator operates. Actual conditions are determined with the help of additional sensors that are part of Smart sensors. As a rule, the assessment is performed by comparing the measured or calculated state with the permissible values under which the correct operation of the equipment occurs.

This significantly allows you to expand the possibilities of existing methods to ensure the solution of the previously mentioned maintenance tasks according to failure prediction.

The structure of the maintenance system according to the actual technical condition of the equipment is represented on figure 1 [6].

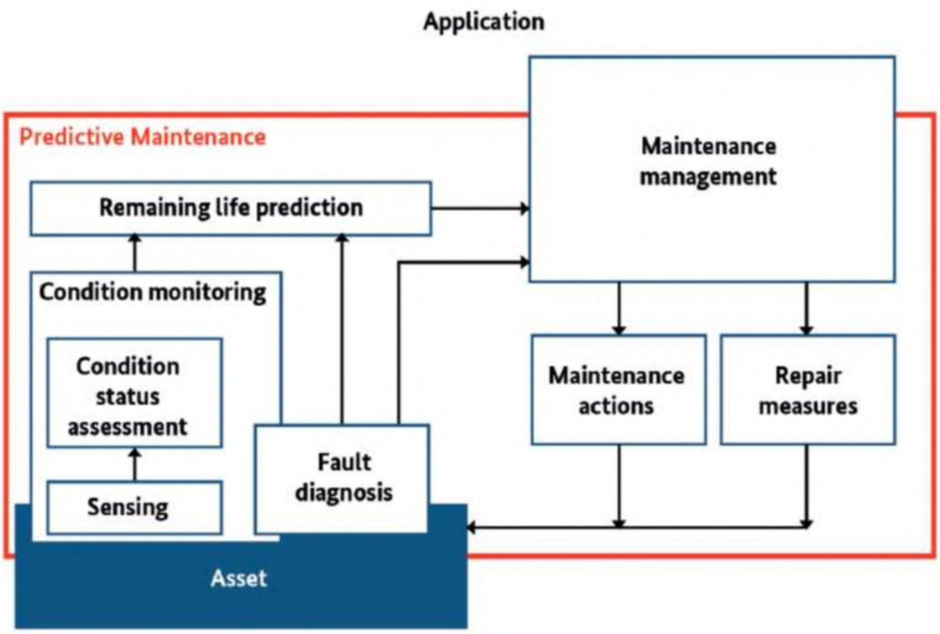

Figure 1. The principle functional structure of fault diagnosis system with predictive maintenance.

3. Physical and mathematical models

For the solution of problem of the remaining useful life prediction of hydro units, it is necessary to build models based on individual quantitative data describing the state of a specific unit of a specific machine, taking into account the history of its use. If there are no physical diagnostic models, the analytical or computer modeling methods are used, which based on the appropriate algorithms [12–17].

Therefore, to elaborate algorithms for the functioning of monitoring and diagnostics systems, it is advisable to use the processes of autoregression (AR process), which have become widely used during the implementation of mathematical models of various types information signals and allow to elaborate algorithms for diagnosing technical objects that have a low frequency of shaft revolutions [18, 19]. A theory of the same processes has been considered in the papers [20–28].

By definition, a stationary linear autoregressive (AR) process is defined as

$$\xi_t + a_1\xi_{t-1} + \ldots + a_p\xi_{t-p} = \zeta_t \tag{1}$$

where $\{a_j, a_j \neq 0, j = \overline{1,p}\}$ are autoregressive parameters; p is the order of autoregressive; $\{\zeta_t, t \in Z\}$ is a stationary random process with infinitely divisible distribution, it has independent values, $P\{\zeta_0 = 0\} = 1$. This process is often called as the generating process. It is assumed that the process is stationary in the narrow sense and ergodic theorems are fulfilled [19].

Linear stationary autoregressive processes can be given by

$$\xi_t = \sum_{\tau=1}^{\infty} \phi_{ar}(\tau)\zeta_{t-\tau} \tag{2}$$

where $\phi_{AR}(\tau)$ is a kernel of the linear AR process [19].

It is assumed that

$$\phi_{ar}(0) = 1; \sum_{\tau=1}^{\infty} |\phi_{ar}(\tau)|^2 < \infty \tag{3}$$

Kernel $\phi_{AR}(\tau)$ is connected with parameters of autoregression [19]:

$$\phi_{ar}(\tau) = \begin{cases} 0 & k < 0 \\ 1 & k = 0 \\ \sum_{\tau=1}^{k} a_\tau \phi_{ar}(k-\tau) & k = \overline{1, p-1} \\ \sum_{\tau=1}^{p} a_\tau \phi_{ar}(k-\tau) & k = \overline{p, p+1} \end{cases} \tag{4}$$

where: $\phi_{AR}(\tau)$ – is a kernel of linear stationary autoregressive process.

The process ξ_t is assumed to be strictly stationary random process, and ergodic theorems are carried out [13]. The process ξ_t has a Kolmogorov representation one-dimensional form logarithm of characteristic function (CF):

$$lnf_\zeta(u,t) = lnf_\zeta(u,1) = im_\zeta u + \int_{-\infty}^{\infty} \{e^{iux} - 1 - iux\} \frac{dK_\zeta(x)}{x^2} \tag{5}$$

where parameter m_ξ and spectral functions of jumps $K_\xi(x)$ define unequivocally the characteristic function of the random process.

It is necessary to remark that special installations are constructed for experimental research [29–36]. A special experimental stand was created at the Institute of Electrodynamics of the National Academy of Sciences of Ukraine. It was used for carry out practical research on vibration analysis. Figure 2 shows a general view of the experimental stand. It was used for research of the influence of the operation of bearing assemblies of electric machines (EM) in different speed modes of its operation on the components of vibration processes that accompany the operation of the machine. The main goal of the research is to experimentally identify the connections between typical defects such as misalignment, eccentricity, lubricant quality, damage to the outer or inner ring of the bearing as a result of metal pitting (pitting) and the parameters of diagnostic signs that clearly allow the defect to be detected.

Figure 2. Installation for vibration tests of bearings.

Experimental setup consists of three parts: an electric drive, a massive shaft, a mounting unit and vibration measurement instruments of the tested bearing. Rotation of the tested bearing, installed in the attachment and vibration measurement unit, is provided by a direct current electric motor of the P-51 type through a massive shaft. Motor 11 kW ensures rotation of the tested bearing at speed is in the range 10 to 1000 rpm. Usage of a special coupling with rubber fingers makes it possible to reduce the vibrations caused by the operation of the electric motor. The reduction of the vibrations of the shaft of the experimental installation is facilitated by usage of sliding bearings. The bearings are made of PTFE. Three units of the experimental installation were placed on a massive plate. The main purpose of the bearing assembly and vibration measurement is the ability to artificially reproduce the main defects of the bearing and the placement of primary vibration-transducing equipment (accelerometers). To measure the vibration accelerations of the bearing under study, an accelerometer type ABC-017 was used, which made it possible to measure the acceleration of vibrations of the bearing in the frequency band of 20 Hz . . . 30 kHz. It is installed in the radial direction in relation to the tested bearing. Research was carried out on rolling bearings of type 309 ESH2 with various types of defects (skew, lack of lubrication, defects of inner and outer rings, rolling bodies caused by metal spalling due to its fatigue). When carrying out experiments on the influence of the angular velocity of EM shaft rotation on quantitative assessments of the main diagnostic features, the speed mode of shaft rotation varied directly with the values $v_{rot} \in (250, 500, 750, 1000)$ rpm. Autoregressive parameters were used as diagnostic features. A bearing misalignment type defect was modeled. Educational groups were formed in the diagnostic space a_1, a_2. Two-dimensional histograms corresponding to the selected test conditions are presented in figure 3 and figure 4.

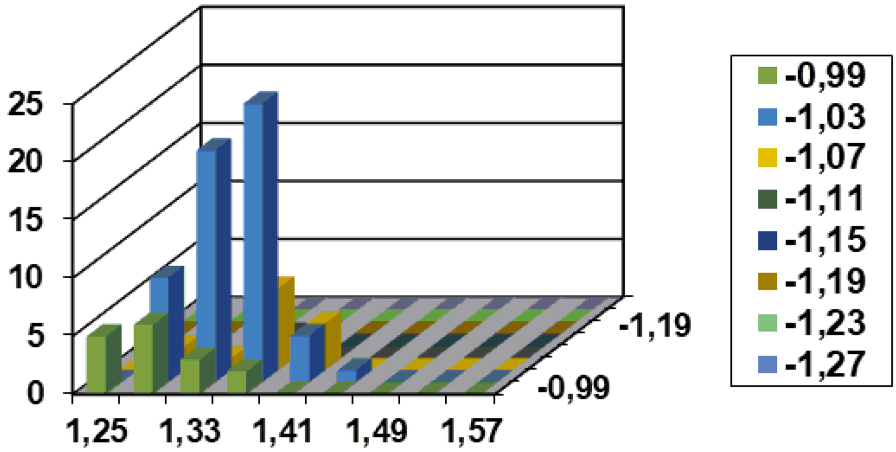

Figure 3. Histogram of diagnostic parameters of the serviceable bearing.

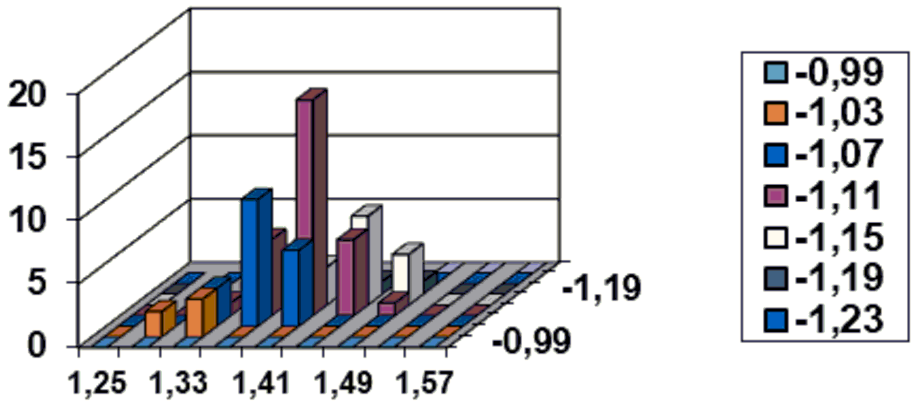

Figure 4. Histogram of diagnostic parameters the misaligned bearing.

4. Algorithms of diagnosis

Figure 5 illustrates algorithm in training mode.

The learning algorithm, first, an evaluation of diagnostic signs is carried out. Then, on the basis of these populations, a vector of estimates of their mathematical expectations, an estimate of variances, and the construction of covariance matrices of correlations between diagnostic parameters and an assessment of the characteristics of the distribution of diagnostic signs were built. If necessary, linear transformations of covariance matrices and normalization of covariance matrices are performed to construct effective decision rules [19].

At the stage of planning the experiment (figure 6), the threshold C and the required number of observations N are calculated.

In the diagnostic mode, diagnostic signs assessed and a decision made on the technical condition of the diagnostic object based on the constructed solving rules (figure 7).

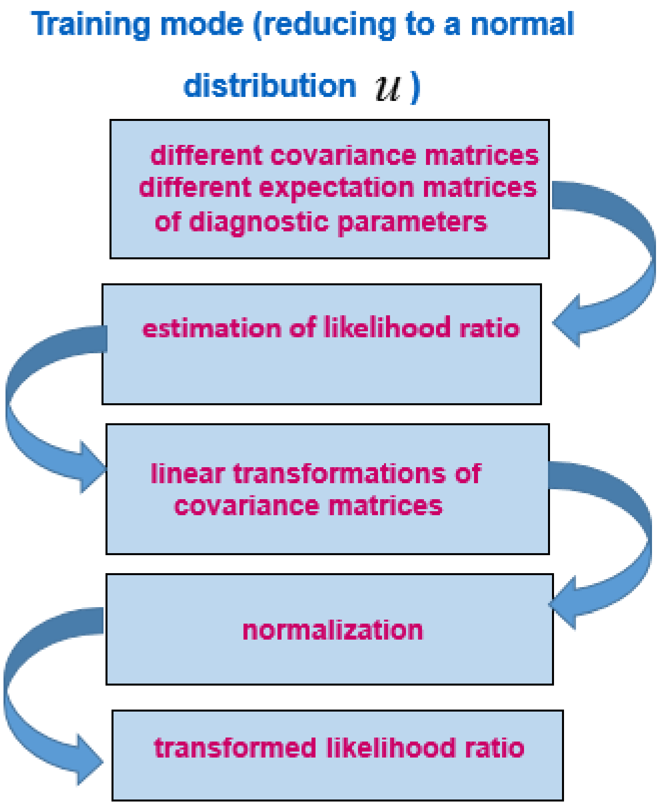

Figure 5. Algorithm in training mode.

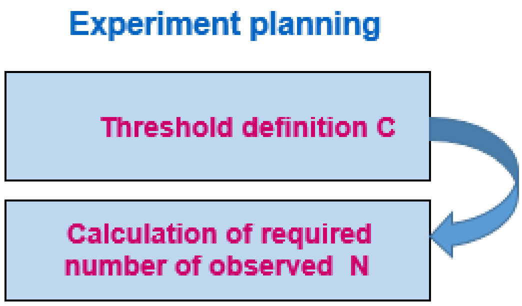

Figure 6. Algorithm in experiment planning.

The proposed forms of presentation of educational aggregates in the relevant training blocks of the EM diagnostic system allow organizing the functioning of such systems using the Smart concept.

5. Conclusions

Solving the problems of diagnosing the technical condition connected with the solutions of the problems, the identification of the processes of genesis of defects and the search for defects of nodes. For the evaluation of diagnostic features, the use of autoregressive processes is proposed. According to the proposed mathematical models, experimental results and with taking into account the standards ISO 19283:2020 and ISO 61850-7-410 algorithms of vibration system for

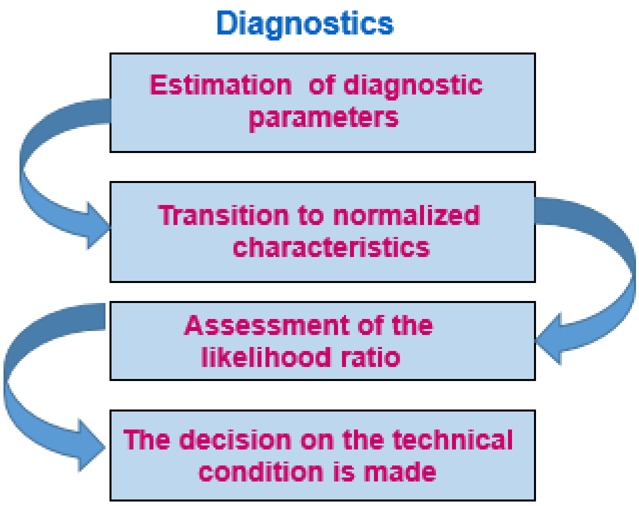

Figure 7. Algorithm in diagnostic mode.

monitoring and diagnosing hydro generators has been developed which enables the functioning of the diagnostic system of the hydro power station by the Smart technology. The possibilities of application showed on the experimental stand. Application results and algorithms used in the system are given. The use of the proposed structures and algorithms make it possible to organize the operation of such systems using the concept of Smart systems.

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References
[1] ISO 2020 *ISO 19283:2020. Condition monitoring and diagnostics of machines — Hydroelectric generating units* (Geneva, Switzerland: ISO copyright office)
[2] ISO 2020 *ISO 61850-7-410. Communication networks and systems for power utility automation – Part 7-410: Hydroelectric power plants – Communication for monitoring and control* (Geneva, Switzerland: ISO copyright office)

[3] ISO 2007 *ISO 13374:2007. Condition Monitoring and Diagnostics of Machines. Data processing, Communication and Presentation; International Organization for Standardization* (Geneve, Switzerland: ISO copyright office)

[4] ISO 2015 *ISO 13381-1:2015. Condition Monitoring and Diagnostics of Machines. Prognosics. Part 1: General Guidelines* (Geneve, Switzerland: International Organization for Standardization)

[5] ISO 2016 *ISO 20816-1:2016. Mechanical Vibration. Measurement and Evaluation of Machine Vibration. Part 1: General Guidelines ISO 79* (Geneve, Switzerland: ISO copyright office)

[6] ISO 2005 *ISO 7919-5:2005. Mechanical Vibration. Evaluation of machine vibration by measurements on rotating shafts. Part 5: Machine sets in Hydraulic Power Generating and Pumping Plants* (Geneve, Switzerland: International Organization for Standardization)

[7] ISO 1998 *ISO 10817-1:1998. Rotating shaft vibration measuring systems — Part 1: Relative and absolute sensing of radial vibration* (Geneve, Switzerland: ISO copyright office)

[8] Baker Hughes Company 2020 Condition monitoring solutions for hydroelectric power generation URL `https://dam.bakerhughes.com/m/65bbcaf2f9e27e6a/ori`

[9] Sino-German Industrie 40/Intelligent Manufacturing Standardisation Sub-Working Group 2018 *The Standardization Roadmap of Predictive Maintenance for Sino-German Industrie 4.0/Intelligent Manufacturing* (Berlin: Federal Ministry of Economic Affairs and Energy, Department of Public Relations) URL `https://www.dke.de/resource/blob/1711308/ad04db2c91a6749c86e7311c1a294644/the-standardisation-roadmap-of-predictive-maintenance-for-sino-german-industrie-4-0-data.pdf`

[10] Zaitsev I, Levytskyi A and Bereznychenko V 2022 Hybrid Diagnostics Systems for Power Generators Faults: Systems Design Principle and Shaft Run-Out Sensors *Power Systems Research and Operation: Selected Problems* ed Kyrylenko O, Zharkin A, Butkevych O, Blinov I, Zaitsev I and Zaporozhets A (Cham: Springer International Publishing) pp 71–98 ISBN 978-3-030-82926-1 URL `https://doi.org/10.1007/978-3-030-82926-1_4`

[11] Zaitsev I, Bereznychenko V, Bajaj M, Taha I B M, Belkhier Y, Titko V and Kamel S 2022 *Sensors* **22**(4) 1634 ISSN 1424-8220 URL `https://doi.org/10.3390/s22041634`

[12] Gul M and Necati Catbas F 2009 *Mechanical Systems and Signal Processing* **23**(7) 2192–2204 ISSN 0888-3270 URL `https://doi.org/10.1016/j.ymssp.2009.02.013`

[13] Widodo A, Kim E Y, Son J D, Yang B S, Tan A C, Gu D S, Choi B K and Mathew J 2009 *Expert Systems with Applications* **36**(3, Part 2) 7252–7261 ISSN 0957-4174 URL `https://doi.org/10.1016/j.eswa.2008.09.033`

[14] Lee J, Wu F, Zhao W, Ghaffari M, Liao L and Siegel D 2014 *Mechanical Systems and Signal Processing* **42**(1) 314–334 ISSN 0888-3270 URL `https://doi.org/10.1016/j.ymssp.2013.06.004`

[15] Huang R, Xi L, Li X, Richard Liu C, Qiu H and Lee J 2007 *Mechanical Systems and Signal Processing* **21**(1) 193–207 ISSN 0888-3270 URL `https://doi.org/10.1016/j.ymssp.2005.11.008`

[16] Chen Y, Liang X and Zuo M J 2019 *Mechanical Systems and Signal Processing* **134** 106342 ISSN 0888-3270 URL `https://doi.org/10.1016/j.ymssp.2019.106342`

[17] Jardine A K S, Lin D and Banjevic D 2006 *Mechanical Systems and Signal Processing* **20**(7) 1483–1510 ISSN 0888-3270 URL `https://doi.org/10.1016/j.ymssp.2005.09.012`

[18] Zvaritch V, Myslovych M and Gyzhko Y 2021 Application of Linear Random Processes to Construction of Diagnostic System for Power Engineering Equipment *Advances in Production Management Systems. Artificial Intelligence for Sustainable and Resilient Production Systems* ed Dolgui A, Bernard A, Lemoine D, von Cieminski G and Romero D (Cham: Springer International Publishing) pp 617–622 ISBN 978-3-030-85874-2 URL `https://doi.org/10.1007/978-3-030-85874-2_67`

[19] Babak V P, Babak S V, Myslovych M V, Zaporozhets A O and Zvaritch V M 2020 Methods and Models for Information Data Analysis *Diagnostic Systems For Energy Equipments* (Cham: Springer International Publishing) pp 23–70 ISBN 978-3-030-44443-3 URL `https://doi.org/10.1007/978-3-030-44443-3_2`

[20] Modaresi Movahed T, Jalaly Bidgoly H, Khoshgoftar Manesh M H and Mirzaei H R 2021 *International Communications in Heat and Mass Transfer* **127** 105565 ISSN 0735-1933

[21] Davis R A and Song L 2020 *Journal of Econometrics* **216**(1) 246–267 ISSN 0304-4076 Annals Issue in honor of George Tiao: Statistical Learning for Dependent Data URL `https://doi.org/10.1016/j.jeconom.2020.01.017`

[22] Moon J, Hossain M B and Chon K H 2021 *Signal Processing* **183** 108026 ISSN 0165-1684 URL `https://doi.org/10.1016/j.sigpro.2021.108026`

[23] Chenoweth T, Dowling K, Hubata R and St Louis R 2004 *International Journal of Forecasting* **20**(1) 41–52 ISSN 0169-2070 URL `https://doi.org/10.1016/S0169-2070(03)00006-2`

[24] Berger D 2020 *Stochastic Processes and their Applications* **130**(10) 5865–5887 ISSN 0304-4149 URL `https://doi.org/10.1016/j.spa.2020.04.009`

[25] Brockwell P J and Marquardt T 2005 *Statistica Sinica* **15**(2) 477–494 ISSN 10170405, 19968507 URL https://www3.stat.sinica.edu.tw/statistica/oldpdf/A15n29.pdf
[26] Davis R A and Song L 2020 *Journal of Econometrics* **216**(1) 246–267 ISSN 0304-4076 Annals Issue in honor of George Tiao: Statistical Learning for Dependent Data URL https://doi.org/10.1016/j.jeconom.2020.01.017
[27] Moon J, Hossain M B and Chon K H 2021 *Signal Processing* **183** 108026 ISSN 0165-1684 URL https://doi.org/10.1016/j.sigpro.2021.108026
[28] Kowalski A and Szynal D 1990 *Journal of Multivariate Analysis* **34**(1) 14–36 ISSN 0047-259X URL https://doi.org/10.1016/0047-259X(90)90058-P
[29] Williams T, Ribadeneira X, Billington S and Kurfess T 2001 *Mechanical Systems and Signal Processing* **15**(5) 979–993 ISSN 0888-3270 URL https://doi.org/10.1006/mssp.2001.1418
[30] Yang H, Mathew J and Ma L 2005 *Mechanical Systems and Signal Processing* **19**(2) 341–356 ISSN 0888-3270 URL https://doi.org/10.1016/j.ymssp.2004.03.008
[31] Lopez I and Sarigul-Klijn N 2009 *Mechanical Systems and Signal Processing* **23**(7) 2287–2300 ISSN 0888-3270 URL https://doi.org/10.1016/j.ymssp.2009.02.014
[32] Brito L C, Susto G A, Brito J N and Duarte M A V 2021 *Informatics* **8**(4) 85 ISSN 2227-9709 URL https://doi.org/10.3390/informatics8040085
[33] Schmidt S, Heyns P S and Gryllias K C 2021 *Mechanical Systems and Signal Processing* **158** 107771 ISSN 0888-3270 URL https://doi.org/10.1016/j.ymssp.2021.107771
[34] Pang S, Yang X, Zhang X and Sun Y 2021 *Mechanical Systems and Signal Processing* **159** 107821 ISSN 0888-3270 URL https://doi.org/10.1016/j.ymssp.2021.107821
[35] Chen Y, Liang X and Zuo M J 2019 *Mechanical Systems and Signal Processing* **134** 106342 ISSN 0888-3270 URL https://doi.org/10.1016/j.ymssp.2019.106342
[36] Soleimani A and Khadem S E 2015 *Chaos, Solitons & Fractals* **78** 61–75 ISSN 0960-0779 URL https://doi.org/10.1016/j.chaos.2015.06.018

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Electricity consumption simulation using random coefficient periodic autoregressive model

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Abstract. The concept of a continuous-time conditional linear random process involves a random kernel being integrated stochastically by a process with independent increments, which is often called a "generative process". In cases where the "generative process" is Poisson, the resulting model represents an investigated signal as a sum of numerous stochastically dependent random impulses each of which occurs according to some inhomogeneous Poisson arrival process. This model can be applied to represent various processes related to energy consumption, such as electricity loads of electrical power systems, gas and water consumption, and other energy resources, while also considering the signals' cyclostationarity, which is usually caused by the rhythmic nature of consumer behaviour. A member of the discrete-time conditional linear cyclostationary random processes class is the random coefficient periodic autoregressive (RCPAR) model, which is appropriate for use in energy informatics, including estimation, forecasting, and computer simulation purposes. The primary objective of the paper is to establish a procedure for simulating the hourly electricity consumption of small and medium-sized enterprises using the RCPAR model, which has periodic parameters and creates cyclostationary properties while also accounting for the investigated process conditional heteroscedasticity. The statistical estimation step of the proposed procedure uses the general methodology for estimating the parameters of the RCPAR model and the methods of statistical analysis of cyclostationary signals. This step is used to identify the simulation characteristics. The simulation step is based on the methods of cyclostationary white noise generation and its transformation by a digital linear filter with random parameters. The last ones are obtained using the Gaussian random vectors computer simulation methods, taking into account the cyclostaionarity property.

1. Introduction

The development of mathematical and computer-based models for stochastic signals, processes, and noises is a crucial step in the creation of information measurement and control systems within the electric power industry [1, 2], as well as automated systems for energy consumption analysis (electric, gas, water consumption), information technology for monitoring and diagnosing the technical conditions and environment of energy facilities, etc. The models form the theoretical foundation for the design and implementation of such systems and technologies, and provide the basis for signal processing algorithms, diagnostic decision-making methods, and energy consumption forecasting. An adequate mathematical model must accurately represent the physical mechanism behind the signal or process, enable theoretical analysis, and facilitate the detection and estimation of informative characteristics of energy objects. Moreover, it should also be suitable for creating computer simulation models to solve practical problems.

Modern problems and challenges in the energy sector, which are associated with the volatility and partial controllability of sustainable energy generators, the uncertainty of the behaviour of energy consumers (which is no longer necessarily in line with traditional load profiles), decentralization, modification of the dynamic characteristics of sustainable energy systems, require comprehensive scientific applied research in the domain of energy informatics, which combines computer science, control systems, and energy management systems in a single methodology [3]. Important areas of energy informatics are the collection, analysis, deployment, and exploitation of energy status data, modelling, simulation, and prediction of the behaviour of energy objects and processes [3], including energy consumption computer simulation. Energy consumption data analysis and simulation are also useful instruments for the problems of user segmentation based on energy consumption behaviour, electricity consumption pattern (load profiles) analysis, power consumption forecasting, etc. Modelling, computer simulation, digital twin technology [4], etc. can be interconnected to create a complex digital energy ecosystem called as "Energy Metaverse" [5].

Mathematical models represented as continuous-time or discrete-time linear random processes (LRP) are very useful for solving the above problems in energy engineering [6, 7]. In the mentioned above application domains, the different implementations of linear periodic random processes [6, 7] are also very useful, which allows taking into consideration the cyclostationarity of the studied signals or processes, caused, for example, by the rhythmic daily (weekly, yearly, etc.) behaviour of electricity, gas, or water consumers, vibrations of the bearings of energy facilities, and other energy objects that are subject to monitoring and diagnosis.

Linear random processes are commonly used for mathematical modeling of signals that are additively comprised of a large number of independently occurring independent impulses (with random parameters) forming a Poisson flow [6]. However, when these impulses are dependent random functions, a more appropriate model would be a conditional linear random process (CLRP) [8], which is defined as a stochastic integral of a random kernel driven by a 'generative' inhomogeneous process with independent increments (LRP has a similar construction, where the kernel is a deterministic function).

For the problems of statistical monitoring, forecasting, diagnostics, and computer simulation, discrete-time LRP is mostly used in the form of an autoregressive sequence, and for cyclostationary processes as periodic autoregression [6, 7, 9]. Similarly, the random coefficient autoregressive (RCA) model [8, 10] is an effective tool for the statistical analysis of CLRP. Properties, methods of the parameters estimation of the RCA model in the case of its stationarity, and corresponding computer simulation methods have been studied by many authors (a comprehensive review of corresponding results is given in [10]). The random coefficient periodic autoregressive (RCPAR) model has been defined as RCA model with periodic coefficients. The periodicity conditions of its moment functions and multidimensional distribution functions have been established. Expressions for estimating the parameters of the periodic autoregression model with random coefficients in the general case have been obtained in [8], and the properties of the estimates have been confirmed by the results of computer simulation modelling.

The primary objective of the paper is to develop the method of computer simulation of electricity consumption using random coefficient periodic autoregressive model.

2. Conditional linear random processes

A real-valued conditional linear random process $\xi(\omega, t),\ \omega \in \Omega,\ t \in (-\infty, \infty)$ (where $\{\Omega, F, \mathbf{P}\}$ is some probability space) has been defined in [11] as follows:

$$\xi(\omega, t) = \int_{-\infty}^{\infty} \varphi(\omega, \tau, t) d\eta(\omega, \tau),\ \omega \in \Omega,\ t \in \mathbb{R}, \tag{1}$$

where Ω is a sample space; $\varphi(\omega,\tau,t),\ \tau,t\in\mathbb{R}$ is a real-valued two-dimensional random field, which is called *kernel*; $\eta(\omega,\tau),\ \tau\in(-\infty,\infty)$ is a stochastically continuous process with independent increments, expectation and variance of this process have the following properties: $\mathbf{E}\eta(\omega,\tau)=a(\tau)<\infty$ and $\operatorname{Var}[\eta(\omega,\tau)]=b(\tau)<\infty,\ \forall\tau$; random field $\varphi(\omega,\tau,t)$ and random process $\eta(\omega,\tau)$ are *stochastically independent.*

The representation (1) exists in the sense of mean-square convergence of the sequence of appropriate integral sums if and only if the following holds [8]:

$$\mathbf{E}(\xi(\omega,t))^2=\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\mathbf{E}\left(\varphi(\omega,\tau_1,t)\varphi(\omega,\tau_2,t)\right)da(\tau_1)da(\tau_2)+\int_{-\infty}^{\infty}\mathbf{E}\varphi^2(\omega,\tau,t)db(\tau)<\infty. \tag{2}$$

If kernel $\varphi(\omega,\tau,t)$ is deterministic function then $\xi(\omega,t)$ is LRP [8].

Conditional (conditionally) linear random process (1) has been characterized for the first time by Pierre [12] for the case of a homogeneous and compensated 'generative' process $\eta(\omega,\tau)$. In particular, Pierre studied the central limit theorem for the sequence of linear functionals from conditionally linear random processes with continuous and discrete time with application to the problems of mathematical modelling of radar clatter.

If defined above random process $\eta(\omega,\tau)$ is a Poisson process, then the expression (1) in the following form:

$$\xi(\omega,t)=\sum_{k=-\infty}^{\infty}\varphi(\omega,\tau_k(\omega),t), \tag{3}$$

where ... $<\tau_{k-1}(\omega)<\tau_k(\omega)<\tau_{k+1}(\omega)<$ ... are the times of jumps of the Poisson process, which are equal to the times of random impulses $\varphi(\omega,\tau_k(\omega),t)$ occurrence ($\varphi(\omega,\tau_k(\omega),t)=0$ if $t<\tau_k(\omega)$), and random functions ..., $\varphi(\omega,\tau_{k-1},t)$, $\varphi(\omega,\tau_k,t)$, $\varphi(\omega,\tau_{k+1},t)$, ... are stochastically dependent (at nonrandom time moments ... $<\tau_{k-1}<\tau_k<\tau_{k+1}<$ ...).

The modelling of power system loads as a linear periodic random process is based on the representation of the studied process expressed as the sum of a numerous independent impulses (with random duration and amplitude) occurring at Poisson moments of time. According to the results of experimental studies [8] it is shown that the processes of electricity consumption of individual households are stochastically dependent. This confirms the adequacy of the CLRP model for the tasks of mathematical modelling, forecasting, and simulation of electricity consumption processes at the level of households, residential areas and enterprises. Moreover, taking into account the cyclic behavior of energy users, it can be shown that the investigated electricity load process will be cyclostationary [9] with a period of $T=24$ hours, that is, n-dimensional ($n\geq 1$) cumulative distribution function $F(x_1,\ x_2,\ ...,\ x_n;t_1,\ t_2,\ ...,\ t_n)=\mathbf{P}\left(\xi(\omega,t_1)<x_1,\ \xi(\omega,t_2)<x_2,\ ...,\ \xi(\omega,t_n)<x_n\right)$ of the random process is periodic by its time arguments [9]:

$$F(x_1,\ x_2,\ ...,\ x_n;t_1,\ t_2,\ ...,\ t_n)=F(x_1,\ x_2,\ ...,\ x_n;t_1+T,\ t_2+T,\ ...,\ t_n+T).$$

Let $\xi(\omega,t),\ t\in(-\infty,\infty)$ be the energy system load, mathematical model of which is represented above as a cyclostationary CLRP. Then

$$\xi_t(\omega)=\int_{(t-1)h}^{th}\xi(\omega,s)ds,\ t\in\mathbb{Z},\ h=\frac{T}{L},\ L\in\mathbb{N}$$

is the discrete-time random process which is equal for each $t\in\mathbb{Z}$ to *electricity consumption* during time interval $[(t-1)h,\ th]$. In particular, if $h=1$ hour, then $\xi_t(\omega),\ t\in\mathbb{Z}$ is *hourly* *electricity consumption.* If $\xi(\omega, t),\ t \in \mathbb{R}$ is cyclostationary continuous-time process with the period of T, then $\xi_t(\omega),\ t \in \mathbb{Z}$ is cyclostationary discrete-time process with the period of L.

Discrete-time conditional linear random process is represented as [8]:

$$\xi_t(\omega) = \sum_{\tau=-\infty}^{\infty} \varphi_{\tau,t}(\omega)\eta_\tau(\omega),\ t \in \mathbb{Z}, \tag{4}$$

where $\varphi_{\tau,t}(\omega),\ \tau, t \in \mathbb{Z}$ is an infinite dimension random matrix (kernel), $\eta_\tau(\omega),\ \tau \in \mathbb{Z}$ is sequence of independent random variables (white noise) with finite variance; $\varphi_{\tau,t}(\omega)$ and $\eta_\tau(\omega)$ are stochastically independent, also in the present paper only the case of centered $\eta_\tau(\omega)$, is considered, that is $\mathbf{E}\eta_\tau(\omega) = 0$, then the series (4) is mean-square convergent if the kernel $\varphi_{\tau,t}(\omega)$ satisfies the condition of $\mathbf{E} \sum\limits_{\tau=-\infty}^{\infty} |\varphi_{\tau,t}(\omega)|^2 < \infty$, $\forall t \in \mathbb{Z}$.

Discrete-time linear random process can be obtained from (4) if $\varphi_{\tau,t}(\omega)$ is nonrandom function.

3. Random coefficient periodic autoregressive model

Our idea of statistical estimation of characteristics of CLRP (4) is founded on the following assumptions. A discrete-time LRP can be represented as the response of a linear digital filter (with non-random coefficients that generally change over time, for example, periodically) to an input signal which is white noise in the strict sense. Very important case for practical applications is linear random process in the form of an autoregressive sequence, which is the output of a recursive digital filter to input white noise.

Discrete-time CLRP (4) can be represented as the output of digital filter with random coefficients (because impulse response $\varphi_{\tau,t}(\omega)$ is random function) on the input white noise $\eta_\tau(\omega)$. If this filter is created so that it has only a recursive structure, then the random signal at its output will be a sequence of autoregression with random coefficients.

Random coefficient autoregressive model of the order $p \in \mathbb{N}$ is represented as follows [8, 10]:

$$\xi_t(\omega) = \sum_{k=1}^{p} (a_{k,t} + \alpha_{k,t}(\omega))\xi_{t-k}(\omega) + \eta_t(\omega),\ t \in \mathbb{Z}, \tag{5}$$

where $\eta_t(\omega)$ is centered strict-sense white noise with the finite variance $\mathrm{Var}\,(\eta_t(\omega)) = \sigma_t^2 < \infty$; $\mathbf{a}_t = (a_{1,t},\ a_{2,t},\ \ldots,\ a_{p,t})'$ is a sequence of vectors of nonrandom coefficients (here and further $\mathbf{A}'$ is a matrix, which is transposed to the matrix $\mathbf{A}$); $\boldsymbol{\alpha}_t(\omega) = (\alpha_{1,t}(\omega),\ \alpha_{2,t}(\omega),\ \ldots,\ \alpha_{p,t}(\omega))'$ is a sequence of independent centered random vectors with the covariance matrices $\mathbf{R}_t = \mathbf{E}(\boldsymbol{\alpha}_t(\omega)\boldsymbol{\alpha'}_t(\omega))$; $\boldsymbol{\alpha}_t(\omega)$ and $\eta_t(\omega)$ are independent.

As we already mentioned above, the most comprehensively studied is the case of the stationary RCA model, for which we have $\mathrm{Var}\,(\eta_t(\omega)) = \sigma_t^2 = \sigma^2$, $\mathbf{a}_t = \mathbf{a} = (a_1,\ a_2,\ \ldots,\ a_p)'$, $\mathbf{R}_t = \mathbf{R}$, that is, characteristics are not time varying.

The discrete-time random process (5) is called random coefficient periodic autoregressive model (RCPAR), if there exists the number $L \in \mathbb{N}$ (period), such that

$$\sigma_t^2 = \sigma_{t+L}^2, \mathbf{a}_t = \mathbf{a}_{t+L}, \mathbf{R}_t = \mathbf{R}_{t+L}. \tag{6}$$

The methods for characteristics estimation of RCPAR model have been studied for the first time by Franses et al [13], but with some boundaries, in particular non-random parameters $a_{1,t},\ a_{2,t},\ \ldots,\ a_{p,t}$ were considered as cosine function with the period L (and the parameters of that functions were estimated), moreover, in their model $Var\,(\eta_t(\omega)) = \sigma^2 = const$, elements of the vector $\boldsymbol{\alpha}_t(\omega)$ are independent and also have constant variances. The method of statistical

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estimation for the RCPAR model in general case have been developed in [8] and can be used for parameters specification for the applied problems of electricity consumption computer simulation.

Thus, having the results of experimental observations (or measurements) of $\xi_t(\omega)$, we need to estimate the elements of the vector $\mathbf{a}_t = (a_{1,t},\ a_{2,t},\ \ldots,\ a_{p,t})'$, $t = \overline{1,L}$, variances $\sigma_t^2,\ t = \overline{1,L}$, and also elements of covariance $(p \times p)$-matrices $\mathbf{R}_t,\ t = \overline{1,L}$. Note that since each matrix $\mathbf{R}_t$ is symmetric, then we need to estimate only $p(p+1)/2$-sized vectors $\gamma_t = vec(\mathbf{R}_t),\ t = \overline{1,L}$ [8].

For the convenience of further explanations, we write (5) in the following form [8]:

$$\xi_t(\omega) = \sum_{k=1}^{p} a_{k,t}\xi_{t-k}(\omega) + u_t(\omega) = \mathbf{x'}_{t-1}(\omega)\mathbf{a}_t + u_t(\omega), \tag{7}$$

where $u_t(\omega) = \sum\limits_{k=1}^{p} \alpha_{k,t}(\omega)\xi_{t-k}(\omega) + \eta_t(\omega) = \mathbf{x'}_{t-1}(\omega)\alpha_t(\omega) + \eta_t(\omega);$ $\mathbf{x'}_t(\omega) = (\xi_t(\omega),\ \xi_{t-1}(\omega),\ \ldots,\ \xi_{t+1-p}(\omega))$.

Let $(\xi_{1-p}(\omega),\ \ldots,\ \xi_0(\omega),\ \xi_1(\omega),\ \ldots,\ \xi_{qL}(\omega))$ be the sample (sample size is equal to $qL+p$) of sequence (7) observations, where $q \in \mathbb{N}$ (number of cycles) and period L are considered to be known.

A two-stage algorithm for estimating the coefficients of the stationary RCA model by the method of least squares has been justified by Nicholls and Quinn [8, 10, 14]. The obtained estimations are consistent and asymptotically normal. The approach for statistical estimating the coefficients of the RCPAR model has been developed in [8], it is based on the above results, but takes into account the cyclostationarity properties of the sequence (7).

Taking into account the periodicity of probability distribution of the process (7) and periodicity of its parameters, let us consider L nested subsequences, that is:

$$\zeta_{l,s}(\omega) = \xi_{(s-1)L+l}(\omega) = \mathbf{x'}_{(s-1)L+l-1}(\omega)\mathbf{a}_{(s-1)L+l} + u_{(s-1)L+l}(\omega),\ l = \overline{1,L},\ s = \overline{1,q}. \tag{8}$$

Every l-th sequence from (8) is stationary (as a function of s) random sequence, moreover, all that sequences are jointly stationary.

Thus, on the first step the least squares method is used [8] to (8) for every $l = \overline{1,L}$ obtaining the estimations $\hat{\mathbf{a}}_l(\omega) = (\hat{a}_{1,l}(\omega),\ \hat{a}_{2,l}(\omega),\ \ldots,\ \hat{a}_{p,l}(\omega))'$, $l = \overline{1,L}$ of non-random parameters of RCPAR model on the following form:

$$\hat{\mathbf{a}}_l(\omega) = \left(\sum_{s=1}^{q} \mathbf{x}_{(s-1)L+l-1}(\omega)\mathbf{x'}_{(s-1)L+l-1}(\omega)\right)^{-1} \sum_{s=1}^{q} \mathbf{x}_{(s-1)L+l-1}(\omega)\xi_{(s-1)L+l}(\omega),\ l = \overline{1,L}. \tag{9}$$

On the second stage, using the estimations $\hat{\mathbf{a}}_l(\omega),\ l = \overline{1,L}$ the following has been obtained:

$$\hat{u}_{(s-1)L+l}(\omega) = \xi_{(s-1)L+l}(\omega) - \mathbf{x'}_{(s-1)L+l-1}(\omega)\hat{\mathbf{a}}_l(\omega),\ l = \overline{1,L}. \tag{10}$$

According to [8] statistical estimations $\hat{\gamma}_l(\omega)$ and $\hat{\sigma}_l^2(\omega)$ of the parameters γ_l and σ_l^2, $l = \overline{1,L}$ have the following form:

$$\begin{gathered}\hat{\gamma}_l(\omega) = \left(\sum_{s=1}^{q} \left(\mathbf{z}_{(s-1)L+l}(\omega) - \bar{\mathbf{z}}_l(\omega)\right)\left(\mathbf{z}_{(s-1)L+l}(\omega) - \bar{\mathbf{z}}_l(\omega)\right)'\right)^{-1} \times \\ \times \sum_{s=1}^{q} \hat{u}^2_{(s-1)L+l}(\omega)\left(\mathbf{z}_{(s-1)L+l}(\omega) - \bar{\mathbf{z}}_l(\omega)\right),\ l = \overline{1,L},\end{gathered} \tag{11}$$

$$\hat{\sigma}_l^2(\omega) = \frac{1}{q}\sum_{s=1}^{q} \hat{u}^2_{(s-1)L+l}(\omega) - \bar{\mathbf{z}}'_l(\omega)\hat{\gamma}_l(\omega),\ l = \overline{1,L}, \tag{12}$$

where $\mathbf{z}_t(\omega) = \mathbf{D}' vec(\mathbf{x}_{t-1}(\omega)\mathbf{x}'_{t-1}(\omega))$, $\bar{\mathbf{z}}_l(\omega) = \frac{1}{q}\sum_{s=1}^{q} \mathbf{z}_{(s-1)L+l}(\omega)$, $l = \overline{1, L}$; $\mathbf{D}$ is a duplication matrix [8] of size $p^2 \times p(p+1)/2$, which are created in the following way: $\mathbf{D}' = \sum_{i=1}^{p}\sum_{j=1}^{i} \mathbf{v}_{ij}(vec(\mathbf{T}_{ij}))'$; $\mathbf{v}_{ij}$ is a vector, consisting of $p(p+1)/2$ elements, among them $[(j-1)p + i - j(j-1)/2]$-th element is equal to one, and other elements are equal to zero $(1 \le j \le i \le p)$; $\mathbf{T}_{ij}$ is a $(p \times p)$-matrix, where (i, j)-th and (j, i)-th elements are equal to one, and other elements are equal to zero.

4. Hourly electricity consumption simulation

The general approach for the computer simulation of electricity consumption based on RCPAR model has been illustrated on the figure 1.

We should emphasize that characteristics of RCPAR model (Setting 2 – Setting 4) have

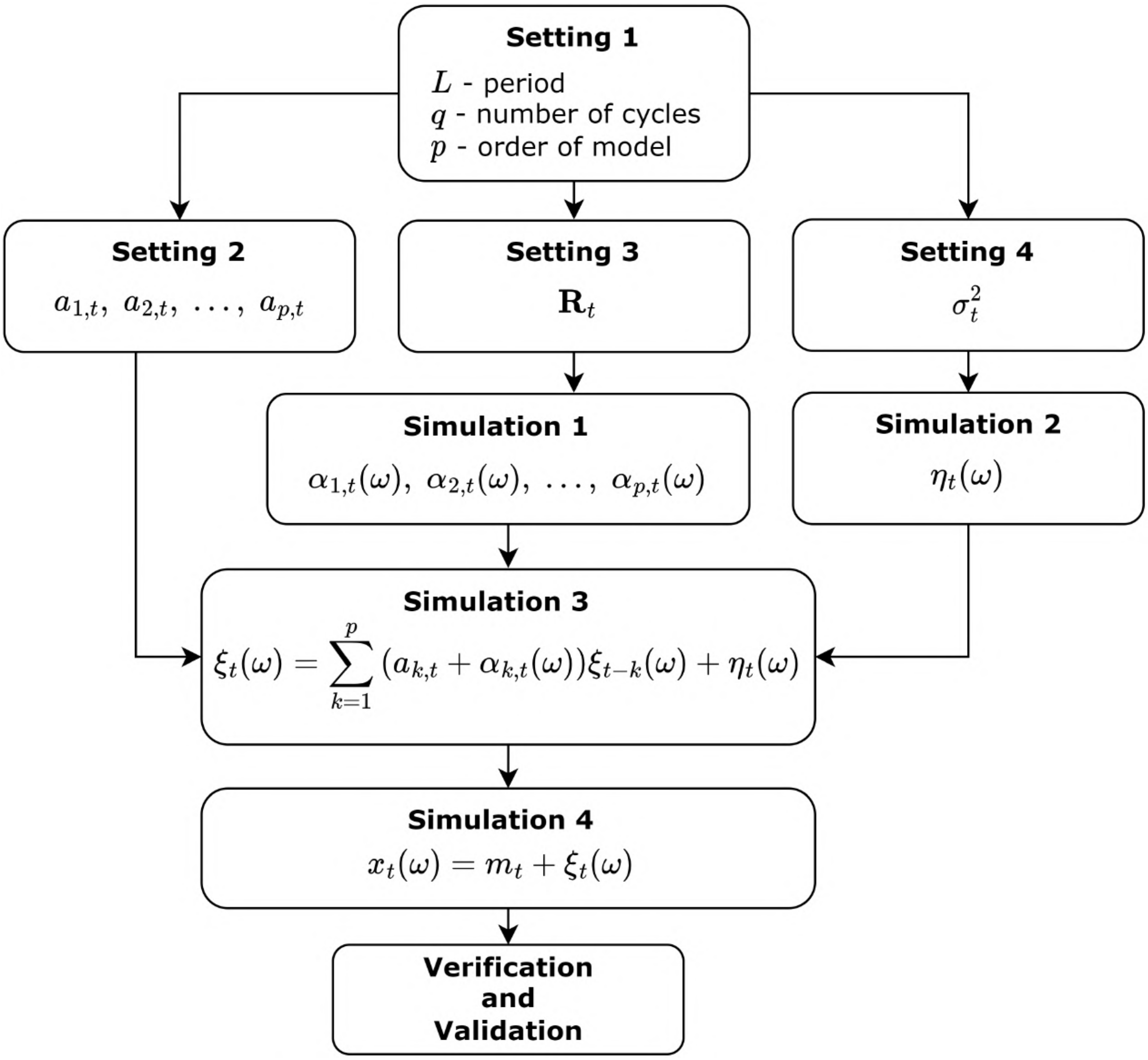

Figure 1. Structure of electricity consumption simulation using RCPAR model.

to be specified as periodic function (see formula (6). The characteristics can be obtained from statistical analysis (estimation step) of electricity consumption data using the expressions (9) – (12). Before performing the estimation procedure according to (9) – (12) the electricity consumption time series data should be centered by the periodic mean estimation (the usual averaging estimator [15] can be used).

In stage Simulation 1 the simulation of centered independent random vectors has to be performed with a given covariance matrix. We recommend generating them as normally distributed random vectors. The method of multivariate normally distributed random vectors simulation is well known and is considered, for example, in [16], we should take into account only that the covariance matrix is time-varying and periodic. That is, according to [16] (section 6.2) step Simulation 1 should be performed for each time stamp in the following way:

- simulation of the vector (the size depends on the order of RCPAR model) of independent standard normal random variables;
- performing the Choleski decomposition of the covariance matrix given in the Setting 3 step;
- simulation of the centered normal random vector (see step Simulation 1), using the linear transformation of the vector of independent standard normal random variables by the lower triangular matrix, which is obtained using the Choleski decomposition.

In stage Simulation 2 the centered white noise should be simulated with periodic variance, given in step Setting 4. The probability distribution is recommended to be normal as well. The well-known methods (e.g. polar method, described in [16], section 5.3) can be used for this simulation, taking into account the time-varying periodic variance of simulated white noise. That is, step Simulation 2 should be performed for each time stamp in the following way: simulation of the standard normal random variable and then multiplying it by the standard deviation given in step Setting 4.

In stage Simulation 3 the RCPAR sequence is simulated using the random objects obtained in the previous steps. Taking into account the mentioned relationship between the random coefficient autoregressive model and digital filters stage Simulation 3 can be performed in the following way:

- design the linear recursive digital filter with random coefficients, given and simulated in steps Setting 2 and Simulation 1;
- feed the white noise from Simulation 2 to the input of this filter;
- output is the computer simulation of RCPAR sequence.

In stage Simulation 4 the deterministic component should be added, which is also a discrete-time periodic function. This function is the mathematical expectation of simulated electricity consumption time series. It has the same period as other above periodic functions.

The verification and validation stages cover checking the computer code for any programming errors, comparing simulated and real data visually (realizations, probability characteristics and parameters) and using the statistical estimations and tests, etc.

The realization of hourly electricity consumption of the enterprise belonging to the category of SME (small and medium-sized enterprises) has been represented in the figure 2 (A). On the same figure 2 below (B) the realization of computer simulation model of the first order has been represented. Mean absolute percentage error (MAPE) is one of the most common performance criteria to validate simulation models [17] and time series forecasting [18]. For the presented example MAPE is equal to 15.12 percent.

We should emphasize the difference between the RCPAR-based computer simulation model of electricity consumption and other close established constructive models such as periodic autoregressive (PAR) model [6, 7] (or more general periodic moving average (PARMA) model

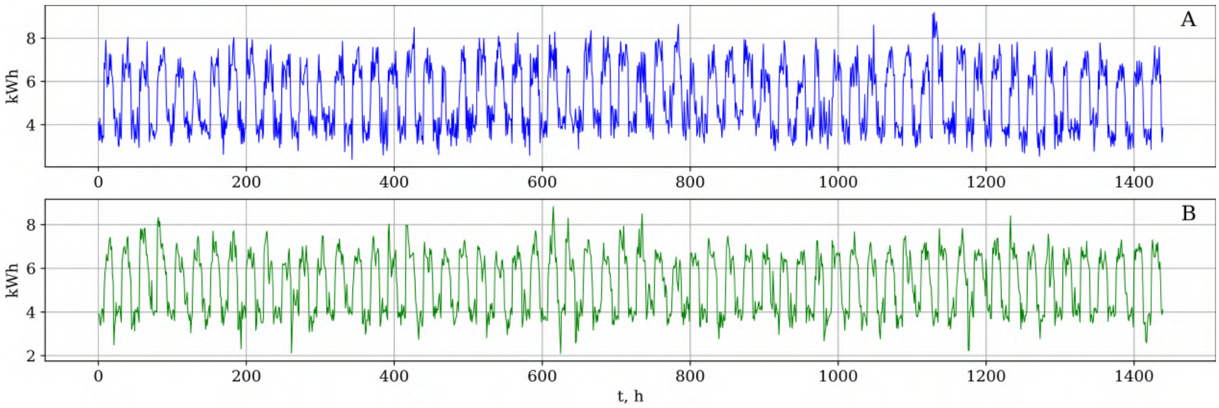

Figure 2. Time series of hourly electricity consumption of SME (A) and its computer simulation model (B).

[6]) and seasonal autoregressive moving average (SARMA) model [18]. All these models can be used both for computer simulation of electricity consumption, as well as for its forecasting. PARMA and RCPAR-based simulation models have periodic parameters, and they are cyclostationary sequences while SARMA is a wide-sense stationary model with constant parameters. PARMA and SARMA models are linear while RCPAR can simulate the nonlinear dynamics representing both periodic heteroscedasticity and conditional heteroscedasticity (random conditional variance) of electricity consumption. Finally, the RCPAR-based computer simulation model follows from a physically reasonable mathematical model of electricity loads in the form of a conditional linear cyclostationary random process. The experimental comparison of the above models is a task for future research.

The prospective research should be also related to estimation (and utilizing in simulation process) of order of the model, which can be periodic function, also the probability distribution of random objects on the stages Simulation 1 and Simulation 2 can be analyzed as different from normal.

The developed computer simulation model as presented above doesn't consider the very important and widespread case of additional weekly (168-hour) cyclicity of electricity consumption, caused, for example, by the days off. A possible way of improvement, in our opinion, is the use of a multivariate random coefficient periodic autoregressive model. For the hourly simulation, the corresponding model would be 24-variate with the period equal to 7.

5. Conclusion

The mathematical model of electricity loads has been represented in the form of cyclostationary conditional linear random process, which made it possible to justify the model of hourly electricity consumption as a cyclostationary discrete-time conditional linear random process.

Random coefficient periodic autoregressive model, as a particular case of discrete-time CLRP, has been used to create the computer simulation method of hourly electricity consumption of SME, taking into account its cyclostationarity (periodic heteroscedasticity) and conditional heteroscedasticity.

The first step of this method is statistical estimation of the periodical characteristics of RCPAR model, taking into account its cyclostationarity. The estimations are then analyzed and used for the simulation model parameters specification. RCPAR-based simulation is performed as digital recursive filtration (with random coefficient) of input cyclostationary white noise.

The improvements of the model are possible in the direction of using the non-gaussian distributions of filter coefficients or input white noise and also taking into account the weekly cyclicity of electricity consumption.

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References

[1] Misconel S, Leisen R, Mikurda J, Zimmermann F, Fraunholz C, Fichtner W, Möst D and Weber C 2022 *Renewable and Sustainable Energy Reviews* **153** 111785 ISSN 1364-0321 URL https://doi.org/10.1016/j.rser.2021.111785

[2] Babak V P, Babak S V, Myslovych M V, Zaporozhets A O and Zvaritch V M 2020 Principles of Construction of Systems for Diagnosing the Energy Equipment *Diagnostic Systems For Energy Equipments* (Cham: Springer International Publishing) pp 1–22 ISBN 978-3-030-44443-3 URL https://doi.org/10.1007/978-3-030-44443-3_1

[3] Schmeck H, Monti A and Hagenmeyer V 2022 *Commun. ACM* **65**(4) 58–63 ISSN 0001-0782 URL https://doi.org/10.1145/3511666

[4] Bayer D and Pruckner M 2023 *Energy Informatics* **6**(1) 8 ISSN 2520-8942 URL https://doi.org/10.1186/s42162-023-00263-6

[5] Ma Z 2023 *Energy Informatics* **6**(1) 3 ISSN 2520-8942 URL https://doi.org/10.1186/s42162-023-00258-3

[6] Babak V P, Babak S V, Myslovych M V, Zaporozhets A O and Zvaritch V M 2020 Methods and Models for Information Data Analysis *Diagnostic Systems For Energy Equipments* (Cham: Springer International Publishing) pp 23–70 ISBN 978-3-030-44443-3 URL https://doi.org/10.1007/978-3-030-44443-3_2

[7] Żuławiński W, Grzesiek A, Zimroz R and Wyłomańska A 2023 *Journal of Computational and Applied Mathematics* **427** 115–131 ISSN 0377-0427 URL https://doi.org/10.1016/j.cam.2023.115131

[8] Fryz M and Scherbak L 2019 *Technical Electrodynamics* **2019** 38 – 47 URL https://doi.org/10.15407/techned2019.02.038

[9] Napolitano A 2020 1 - Characterization of stochastic processes *Cyclostationary Processes and Time Series* ed Napolitano A (Academic Press) pp 3–35 ISBN 978-0-08-102708-0 URL https://doi.org/10.1016/B978-0-08-102708-0.00012-1

[10] Regis M, Serra P and van den Heuvel E R 2022 *Econometric Reviews* **41**(2) 207–230 URL https://doi.org/10.1080/07474938.2021.1899504

[11] Fryz M, Scherbak L, Karpinski M P and Mlynko B 2021 Characteristic Function of Conditional Linear Random Process *Proceedings of the 1st International Workshop on Information Technologies: Theoretical and Applied Problems 2021, Ternopil, Ukraine, November 16-18, 2021* (*CEUR Workshop Proceedings* vol 3039) ed Lytvynenko I V and Lupenko S A (CEUR-WS.org) pp 129–135 URL https://ceur-ws.org/Vol-3039/short40.pdf

[12] Pierre P A 1971 *SIAM Journal on Applied Mathematics* **20**(3) 449–461 ISSN 00361399 URL https://doi.org/10.1137/0120048

[13] Franses P H, van der Leij M and Paap R 2002 *Journal of Applied Econometrics* **17**(5) 601–616 ISSN 08837252, 10991255 URL http://www.jstor.org/stable/4129274

[14] Nicholls D F and Quinn B G 1982 *Random Coefficient Autoregressive Models: An Introduction* (New York, NY: Springer US) ISBN 978-1-4684-6273-9 URL https://doi.org/10.1007/978-1-4684-6273-9

[15] Dudek A E 2018 *Journal of Nonparametric Statistics* **30**(1) 87–124 URL https://doi.org/10.1080/10485252.2017.1404060

[16] Ross S 2022 *Simulation* 6th ed (Academic Press)

[17] Hora J and Campos P 2015 *Expert Systems* **32**(5) 578–595 URL https://doi.org/10.1111/exsy.12111

[18] Hyndman R J and Athanasopoulos G 2021 *Forecasting: principles and practice* 3rd ed (Melbourne, Australia: OTexts) URL https://otexts.com/fpp3

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PAPER • OPEN ACCESS

Atmospheric dispersion modelling and dose projection under high uncertainty conditions

Atmospheric dispersion modelling and dose projection under high uncertainty conditions

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Abstract. Understanding the overall magnitude of the deviations that may occur within the results of one or more codes allows avoiding discrepancies in decision making in the context of emergency preparedness and response. The uncertainty of the assessment input data plays a significant role in this. Currently, emergency centers around the world use a number of atmospheric dispersion modelling and dose projection tools that have the same functionality, are used for the same purpose, but may produce different results. This article reveals the problem of uncertainty in the results of atmospheric dispersion modelling and dose projection, which are laid down at the stage of input data for actual software products and decision support systems. The paper lists the main factors that can affect the uncertainty of the assessment results. On the example of the JRODOS system, possible options for describing the source for the spectrum of emergency events at NPPs are considered. Special attention is paid to assimilation of radiation monitoring results and response to hostilities.

1. Introduction

Modern approaches to the emergency response to radiation accidents at nuclear facilities worldwide are coherent. They aim to prevent human losses and establish control over the source of releasing radioactive substances. Mechanisms and procedures for responding to similar accidents are not designed for casualties of a terrorist or military nature, taking into account the principle of peaceful use of atomic energy. The existence of software evaluation tools and decision-making support systems for population protection during radiation accidents is no exception. These tools are the most effective if they provide the full range of input parameters to run the models [1, 2]. However, the response procedures require decision-making based on incomplete data or within the scope of information currently available to the decision-maker in unforeseen conditions.

Today, world emergency centers use modern assessment tools such as the European ARGOS system [3] or the American regulatory RASCAL software complex [4]. The development of a complex real-time decision support system for off-site response to radiation accidents RODOS has been actively supported and coordinated since the beginning of the 90s within the framework of the European Commission's scientific programs. The Java version of this system is called JRODOS [5]. Currently, the further development of this product is continued. Its improved versions are periodically presented by the leading developer of JRODOS – Forschungszentrum Karlsruhe GmbH – on behalf of the JRodos Developers Consortium. It includes 15 institutions from different European countries. Since 2013 this system has been successfully used in the emergency centers of Ukrainian NPPs and regulatory body during emergency response measures for nuclear and radiological accidents. The JRODOS system consists of several mathematical models and databases for conducting predictive calculations on the consequences of possible radiation accidents and planning urgent and early countermeasures for protecting the public. This system is increasing the technical and strategic capabilities of responding to national and cross-border emergencies. The JRODOS models and databases can be adapted for different characteristics of the NPP location and geographical, meteorological, and environmental conditions. Using this system in a state of continuous arrival of numerical weather prediction data, timely information on the chronology and activity of the release allows prompt forecasting of radiological consequences on local and global spatial scales.

2. Uncertainties problem

Some decision support systems (DSS) have a flexible interface and allow to specify output data of the simulation in several ways. Variability of the data entry approach facilitates prompt response to incomplete information regarding the state of the affected object. The package of the primary input data includes source term data, meteorological conditions, calculation settings, and desired results list or their format.

Figure 1 presents the impact of uncertainties regarding the release under unstable meteorological conditions. Case zoes for taking immediate countermeasures for population protection in the case of a severe accident may differ significantly depending on the release moment.

The magnitude and radionuclides mixture are distinguished in addition to the chronological uncertainty of the temporal distribution of emissions. It may also differ significantly and depend on the initial activity of the dose-forming radionuclides in inventory. Currently, various views are considered in the framework of many international projects. This type of uncertainty can be significantly leveled at the stage of emergency preparedness by comparing existing approaches, such as [6], unlike the chronological one.

The World Meteorological Organization investigates uncertainties associated with the numerical data of the meteorological forecast [7]. Some modern DSS allows analyzing of consequences of cases for several variants of meteorological conditions or source terms. Such studies make it possible e to determine the influence of the forecast quality on the final result. It includes zone configuration for the adoption of urgent countermeasures for population protection. In practice, comparative analysis of the calculation results obtained by various organizations is carried out mainly within the framework of international projects and less often within the framework of special emergency exercises. The work [8] contains a list of examples and approaches for comparing results obtained using different codes or DSS.

3. Radionuclide vector, physical and chemical forms

Radionuclide mixes and physicochemical forms of release depend on a complex of factors such as activity of radionuclides in the reactor core and spent fuel pool, features of safety systems, phenomenological stage of fuel damage, etc. Grouping by physico-chemical classes describes the behavior of radioactive vapor-gas mixture within containment. More generalized distribution of radionuclides by physico-chemical forms is also characteristic at the modeling stages of the

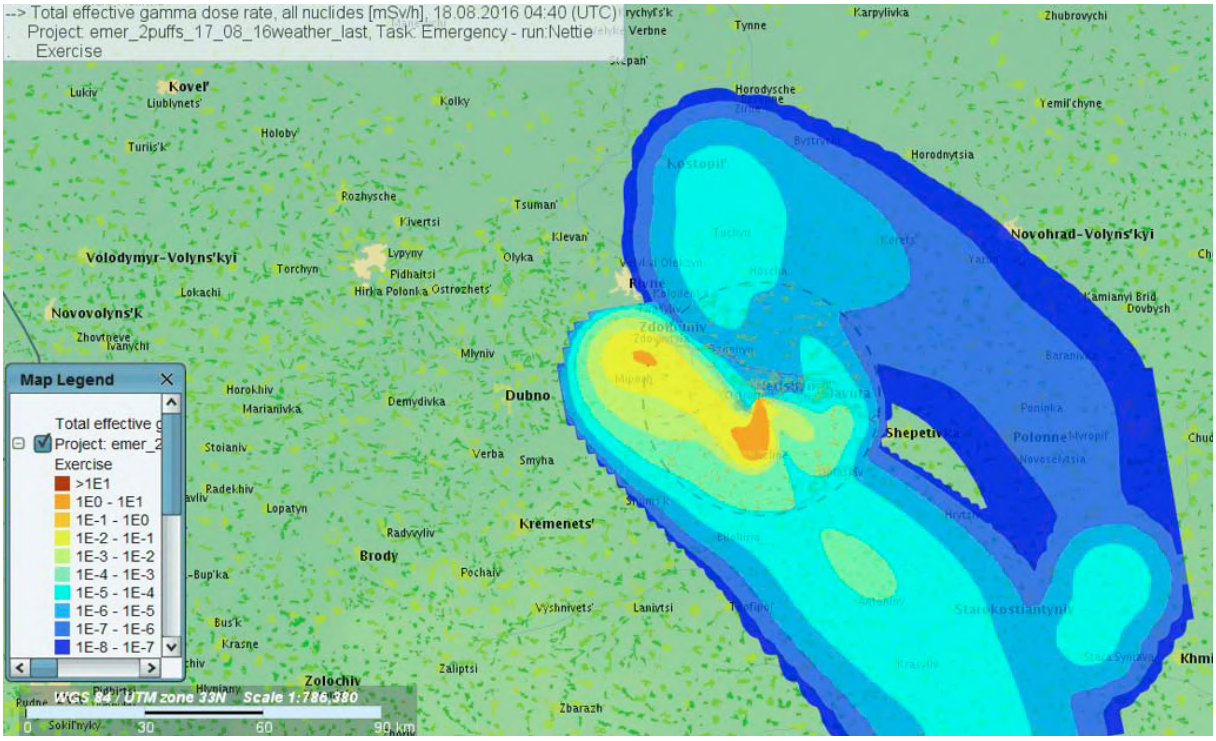

Figure 1. Chronological uncertainty effect.

atmospheric path of distribution and transport along food chains – nobel gases, aerosols, and organic and molecular forms of iodine. Moreover, the same radionuclide (for example, ^{131}I) in different forms has a different nature of deposition on the underlying ground surface. It also plays a different role in dose formation for different pathways of exposure.

Several mathematical models based on the processes of heat and mass transfer and aerodynamics are used to describe radionuclides transport in the closed emergency room of nuclear enterprises. These models are part of integrated calculation software products such as MELCOR [9], MAAP, CONTAIN, etc. These codes use analytical and numerical solutions, operating with empirical and semi-empirical relations. Transport of nuclear fuel fission products is described; the power and composition of the emission of radioactive substances from the premises of emergency objects into the atmosphere are calculated with the help of such tools. The leading representatives of integral codes of this group have a similar structure and cover the main stages of modeling the transport of radioactive substances in process rooms for most design and post-design accidents that are considered during the safety analysis of nuclear power plants.

For example, MELCOR [9] is an integrated computer code at the engineering level. It stimulates the severe accident at a nuclear power plant with light water reactors. This code was developed at Sandia National Laboratories for the US regulatory body. The International Atomic Energy Agency (IAEA) member countries, including Ukraine, actively use this code. MELCOR allows the simulation of a wide range of emergency processes at a nuclear facility. The code enables modeling the transport of fission products along with such processes as the thermal-hydraulic reaction of safety systems and adjacent structures, degradation and movement of fuel masses, the interaction of core melt with concrete of building structures, generation, transportation, and combustion of hydrogen, etc. The modeling basis with this code is a nodalization scheme. It is a spatial division of the power unit objects into separate

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volumes according to the principle of priority of this or that equipment/room contribution to the determining parameters of the emergency process. Thermal-hydraulic parameters within the same book at a particular moment are considered the same—chemical properties group MELCOR fission products. The behavior of chemical elements and their isotopes is regarded as the same within the same class.

There are the following ways of obtaining data on the radionuclide mix in a radioactive release:

1) receiving information from actual measurement points of releases control subsystem (vent stack);
2) use of the general JRODOS library for the formation of source term;
3) analytical assessments of source term according to the phenomenological stages of fuel damage.

The other two paths are preferred but not mandatory if the information provided by the first path is sufficient for the current calculations in the JRODOS system. During the shortage of information (whole or partial), using the two named ways of data formation is necessary.

Initial data for the source term estimating are data on reactor inventory, or data on the radionuclide vector and activity of the coolant, in the absence of more than normative damage to the occupied zone [10, 11]. Data from the JRODOS general library can be used to generate data. It should contain source term according to defined chronological stages:

- coolant release;
- gas gap release;
- fission products release due to partial fuel damage of the reactor core;
- fission products are released due to reactor core melting (in-vessel and ex-vessel phases).

Parameters of the release during accidents with different degrees of damage to the reactor core are determined by several chemical elements and the site of their release into the coolant in case of reactor core damage. The document NUREG-1465 [12] provides information on the approximate relative share of the fission products released from reactor core into the containment air space at various stages of fuel damage for PWR and BWR-type reactors.

Special attention is paid to the distribution of iodine radionuclides during the assessment of the release parameters. This radionuclide is a dose-forming radionuclide by the physicochemical forms of the most critical pathway of exposure. It is necessary to consider the distribution of iodine according to its physical and chemical conditions to determine the rate of dry deposition and the iodine washing from the radioactive cloud. The JRODOS system makes it possible to take into account three forms of iodine:

- aerosol (CsI);
- elementary/molecular (I_2);
- organic (CH_3I).

In modern approaches to realistic forecasting of the radiological consequences of accidents at water-water reactors, the following distributions are distinguished according to 2 ways of exiting the vapor-gas mixture: containment and a fast-acting reduction unit for releasing steam into the atmosphere. A higher amount of organic iodine distribution is chosen for a conservative assessment (especially for transboundary transport).

4. Leakage pathways

Radionuclides can bypass such a barrier as containment during an accident. They can also first enter the air space of the containment and only then enter the environment due to the leakage of the containment (figure 2). The first pathway of propagation is typical for accidents caused by the flow of the primary circuit into the second (failure of steam generator collector). At the same time, radionuclides bypass the containment, immediately entering the second circuit and entering the atmosphere without purification. Another path of propagation is characteristic of accidents associated with the rupture of pipelines of the first circuit up to the maximum design accident.

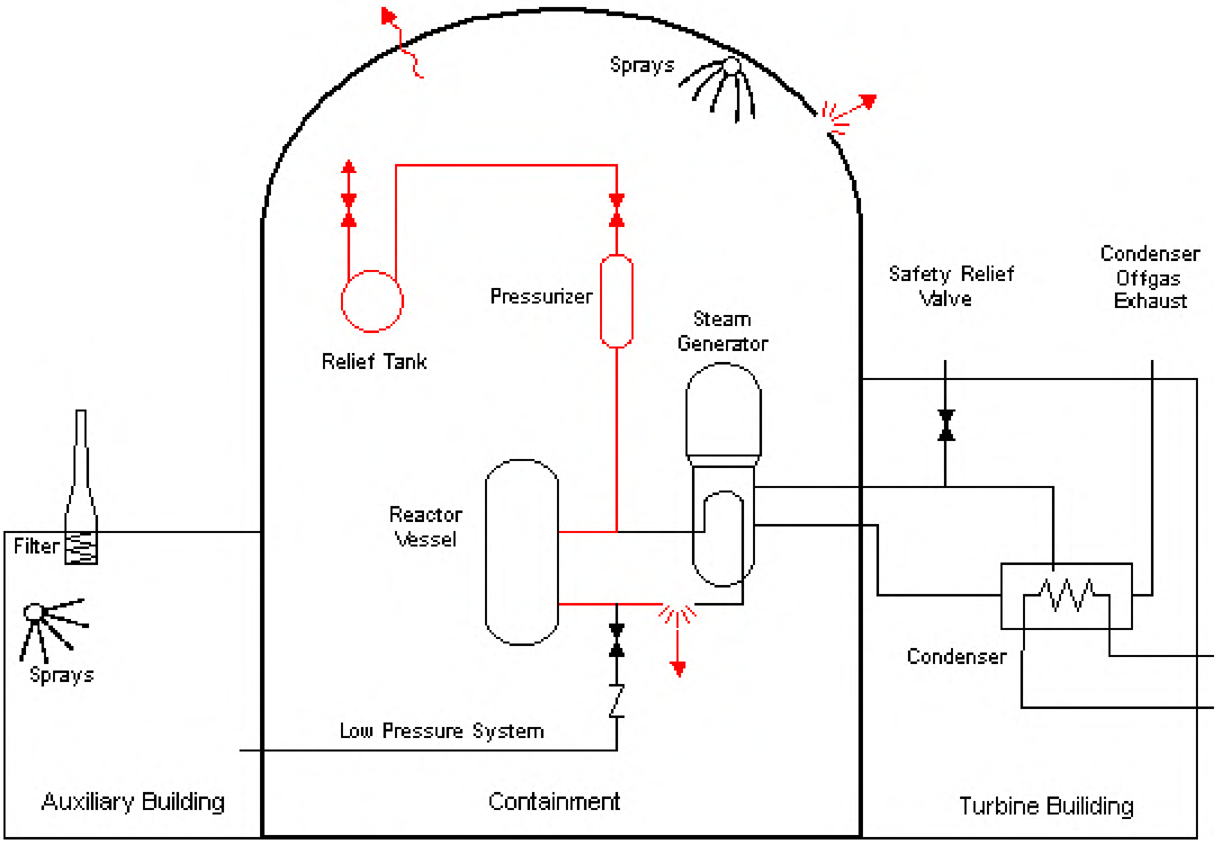


Figure 2. Leakage ways scheme of the steam-gas mixture.

It is necessary to consider the presence or absence of retenrtion to correctly assess the radionuclides released from the containment to the environment. The discharge may be subjected to various mechanisms of retention of radionuclides by safety systems (sprinkler system, bubbling) and under the influence of natural retention mechanisms (sedimentation, decay), depending on the release pathway. At the same time, the activity depends on the length of radionuclides delay before the release. The retention factor refers to the activity ratio of iodine and long-lived aerosols released into the environment to the activity created due to the accident (data from NUREG-1228 [6]).

The efficiency of the filtering system through which the vapor-gas mixture passes is considered in the case of emissions after cleaning with filtering means. It happens if their efficiency is preserved during the course of the accident. At the same time, radioiodine distribution by physicochemical forms changes dramatically. Practical calculations show that the dose-forming groups will be noble gases (Kr, Xe) and organic compounds of radioiodine during accident scenarios with operating filtered containment venting system (FCVS). At the same time, in such methods, the delay time before release into the atmosphere plays a significant role in the radiological consequences results.

Speed radionuclides entering the containment depend on a containment leakage rate. The following intensities of leakage from the containment are accepted in international practice:

- 0.1 – 0.3%/day (normal leakage for PWR-type reactor containments, 0.3%/day – VVER-1000);
- 100% per day (failure of containment isolation valves);
- 100% per hour (corresponds to the containment destruction of).

The delay time of radionuclides before the release into the atmosphere is a determining factor in the calculation of poblic exposure doses in the part of external exposure from nobel gases (dose from the cloud) and radioiodine (dose from inhalation). It is possible to find the activity at any time after the shutdown of the reactor or movement of the steam-gas mixture at any time of its exposure in the free space of the containment knowing the inventory at the end of compaign.

5. Effective release height

Methodological approaches to assessment of the effective release height in various literary sources are presented quite ambiguously. However, we note that all these approaches introduce the following concepts:

- release from tall pipes;
- release from low pipes (guideline №. 50-SG-S3 of the IAEA [13]).

The dawnwash effect can be also considered (estimation of the initial parameters of the atmospheric dispersion) in the second case to increase the realism degree of the calculation.

The plumerise as a component and as a result of the heat energy of the release according to the current parameters is defined by the pre-programmed calculation procedures (Mathcad/Excel) as a part of the real-time calculation. They are used regarding to the IAEA method № 50-SG-S3 for cases:

- unstable and neutral stability class (medium and high boundary of the mixing layer);
- for conditions of a stable atmosphere (low boundary of the mixing layer).

It should be noted that reducing the effective height of the release increases the degree of conservatism in the assessment results of radiological consequences in near range.

The JRODOS system allows the setting of the total release height. It considers the plume rise as a dynamic component and a result of the heat energy of the release. It uses the additional parameters: thermal power of the release, vertical flow rate, and cross-sectional area (nozzles, vent stacks, etc.).

6. Types of input data entry

Modern DSS have a reasonably flexible policy for entering initial data. It allows entry of the source term in terms of release fractions and reactor core inventory at the time interval or the integral release activity without reference to reactor core inventory.

Modern DSS is moving to the IRIX (International Radiological Information Exchange, [14]) format source library standard. The standard significantly facilitates data exchange between organizations and in an international context (table 1).

Table 1. Types of source terms by methods of input data entry on the share/activity of the emission of modern DSS JRODOS [5].

Data entry type	Description
F1	Release fraction [%] on the time interval from the initial activity in the fuel (reactor core inventory).
F2	Released activity [Bq] on the interval from the list of the JRODOS radionuclides.
F3	Released activity [Bq] on the time interval for ^{131}I and the sum of activity for noble gases and aerosols (including the possibility of distribution setting by aerosol fractions).
F4	Released activity [Bq] on the time interval for iodine, noble gases, and aerosols (including the possibility of distribution setting by fractions of aerosols).
F5	Released activity [Bq] on the time interval individually for each nuclide concerning the reactor core inventory.
F6	Released activity [Bq] on the time interval individually for each nuclide without reference to the reactor core inventory.
F7	Activity release rate [Bq/s or Bq/h] on the interval individually for each nuclide without reference to the reactor core inventory.

TECDOC-955 was one of the first international documents covering the systematization of source temrs for NPP severe accidents. The source selection algorithms are based on the events tree concept according to branching criteria. It corresponds to the factors affecting the release intensity (power unit status, operation of safety systems, retention and filtration of the vapor-gas mixture, etc.). Such algorithms are implemented in the International InterRAS system and its subsequent evolution as a software product, RASCAL.

7. Assimilation of radiation monitoring data

Application of radiation measurement data near the emergency power unit (monitoring grid, mobile vehicles, etc.) contributes to the validation of the model and the results confirmation of atmospheric dispersion modeling and dose projection. However, these systems may be partially unavailable in the case of military attacks or occupation. The reliability of the information provided by the radiation monitoring stations remains a separate issue.

Ukraine still needs an integrated automated monitoring system for detecting, analyzing, and forecasting possible radiological consequences of accidents. Accident release may spread beyond the sanitary protection zones of nuclear power plants, other atomic installations, and radiation-hazardous objects in Ukraine and beyond. However, the development of an integrated automated radiation monitoring system is planned until 2024 [15].

There are currently many challenges to developing real-time radiation impact assessment tools. Now, one of the ambitious directions of DSS development is solving the inverse problem of determining coordinates and characteristics of the emission source based on the results of field measurements. The practice of calculations for a wildfirefire in the Chornobyl exclusion zone shows that it is usually possible to estimate the integral characteristics of the release quite quickly if measurement data are available in the near range. However, this procedure requires considerable time to collect and process data to provide an inversion calculation in relatively large spatial scales.

Conducting inverse modelling for events on a large spatial scale requires the involvement of specialized software tools and separate methodological approaches. In addition, the task is complicated because the format and completeness of the output data are individual in each case. Also, there currently needs to be methodical approaches regarding the consideration of radiation monitoring data in the constructed models of atmospheric dispersion of the DSS and its subsequent correction or refinement in real-time. The issue of forming universal approaches to inverse modelling remains open.

8. The problem of forecasting radiological consequences of military causes

The emergency preparedness and response phases are divided by the principle criteria (an announcement of the event class) according to the current IAEA classification for peacetime conditions. The classification of events as objects of the first threat category (for example, nuclear power plants) under martial law declared is not regulated by national or international regulations. It can be assumed that the situation around the Zaporizhzhia NPP is intermediate, given the repeated activation of Ukraine's crisis center's regulatory body during the first nine months of the full-scale invasion. It includes synthesizing elements of both the readiness and the response phases. Some examples of air mass movement trajectories modeling for the Zaporizhzhia NPP are presented in fig.3.

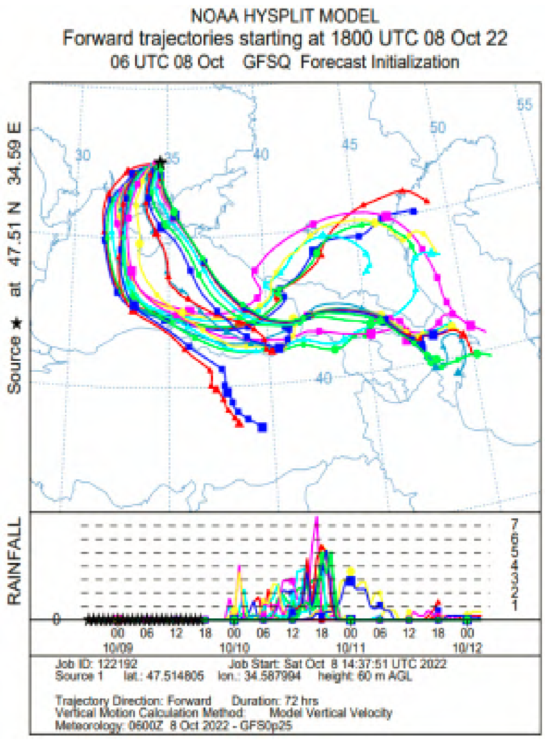
Today there is no experience in international practice on performing safety analyzes of nuclear installations under the war conditions. It includes a lack of methodology and initial data for their conduct (intensity of shelling, degree of damage to buildings and structures from the impact of various types and calibers of ammunition, action personnel, and population behavior in conditions of hostilities and extreme stress, etc.).

Several conditional reference scenarios of severe damage to the reactor core at the VVER-1000/B-320 type reactor plant were considered a representative event for NPP industrial sites considering the above. The creation of the emissions library made it possible to simulate multi-unit scenarios, such as total station blackout for all power unit on-site.

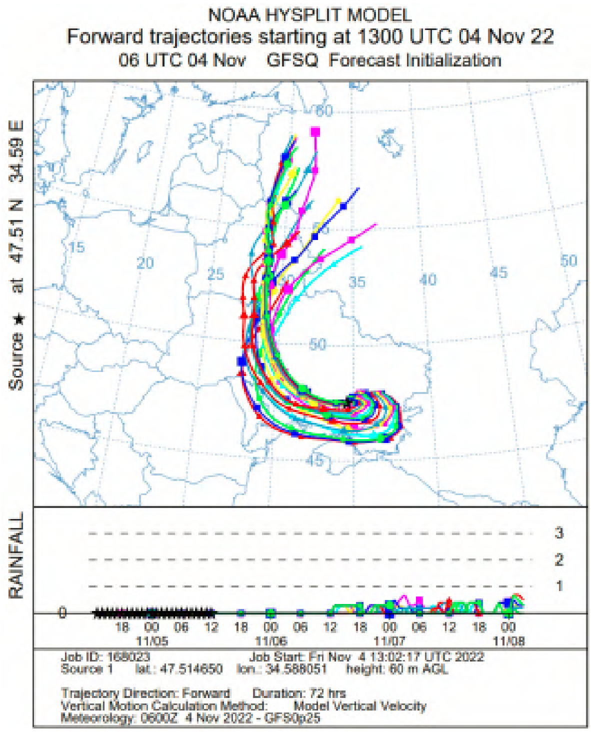
Also, the accident at a spent nuclear fuel dry storage facility was considered, given the assumption of a possible mechanical destruction of spent fuel cask (as a result of hostilities or a terrorist attack), additionally for the Zaporizhzhia NPP. It was considered for one VSC-24 container containing 24 spent fuel assemblies with a minimum spending time of 5 years.

The question of the results ambiguity of atmospheric dispersion modeling and the prediction of radiation doses is based on several uncertainty factors from the input information to the endpoints report on the results. The following can be distinguished among them:

- detail and completeness of input data for assessment and analysis of the situation (state of the nuclear installation, source term, pathway and effective height of the release, time resolution, physical and chemical forms, number of calculated radionuclides, etc.);
- provider and completeness of parameters of numerical weather data of (spatial and temporal resolution, completeness of the list of meteorological parameters);
- atmospheric dispersion model and parameterization;
- dose models, number of reference groups by age, exposure routes;
- model of countermeasures, form, and completeness of the final results presentation of the assessment or forecast (scale, data format, deterministic or probabilistic interpretation);
- type and completeness of accompanying databases (height of roughness of the underlying ground surface, population density, land use, types of shelters, features of the infrastructure, dose coefficients, etc.);
- degree of experience and qualification of the expert.



a)



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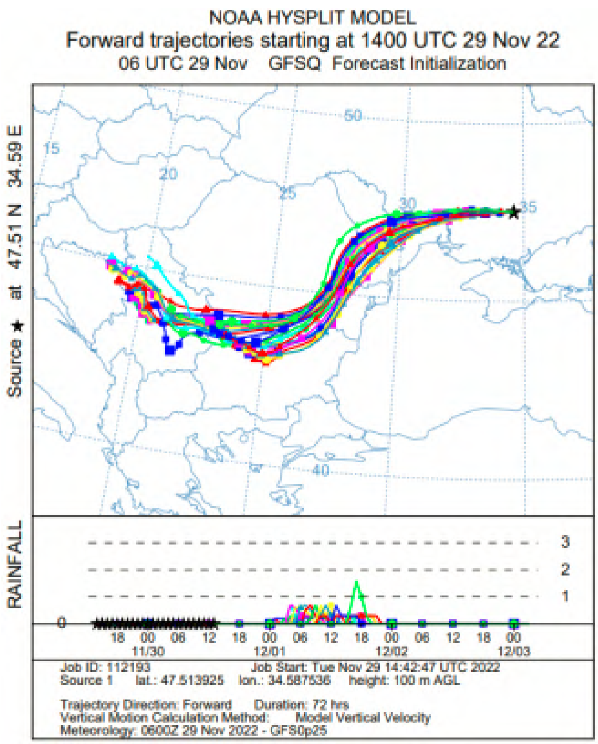

c)

Figure 3. Examples of modeling trajectories of air masses leaving the industrial site of Zaporizhzhya NPP using software HYSPLIT: 08.10.22 (a); 04.11.22 (b); 29.11.22 (c) [16, 17].

9. Author contributions

The research results presented in this publication are the culmination of the collective efforts and distinct contributions of each author:

- *Volodymyr O. Artemchuk*: Conceived the research idea, provided the rationale for its relevance, and played a pivotal role in drafting the article. Additionally, contributed to the formulation of key conclusions.
- *Yurii O. Kyrylenko*: Conducted extensive research on the radionuclide composition and the physical and chemical forms involved. Developed a comprehensive diagram illustrating the paths of steam-gas mixture leakage and contributed significantly to the corresponding report.
- *Iryna P. Kameneva*: Undertook a comprehensive review of contemporary assessment tools used in global crisis centers, providing valuable insights. Focused on the intricate issues of uncertainty and conducted research related to the assimilation of emergency monitoring data.
- *Valeriia O. Kovach*: Conducted in-depth studies aimed at determining the effective height of discharges and provided detailed descriptions thereof. Furthermore, played a significant role in defining input parameters.
- *Andrii V. Iatsyshyn*: Supported the justification of the research's relevance and played a crucial role in conducting research related to the prediction of radiation consequences in military events. Additionally, contributed to the formulation of key conclusions.

Each author's unique expertise and dedication have been instrumental in the completion of this research, enriching its depth and breadth.

10. Conclusions

Consequences of acts of nuclear terrorism or military attacks on nuclear facilities may significantly impact the public and environment. They are associated with high uncertainties or insufficient initial data for calculations. Modern emergency preparedness and response modeling tools (as DSS) are not designed for use under conditions of such uncertainty.

At the same time, there are many methodical approaches to the deriving source term during accidents accompanied by significant release of radioactive substances into the environment. These approaches help to approximate and sometimes re-analyze a dynamic picture of radionuclide concentrations in the air and total fallout. They also allow the conduct of comprehensive assessment on impact on the public and environment. A review of their application features showed that the development of approaches to the source term description is an effective tool for providing initial data in various variants and forms necessary for calculating radiation consequences in DSS and other software tools.

The main characteristics of the source term represent a package of initial data for modeling atmospheric dispersion and dose projection during a severe accident at a nuclear power plant. It was found that there needs to be a universal methodology and procedures for responding to events with a high degree of uncertainty, particularly in the data regarding the source term.

The problem of uncertainties requires further research and analysis from the point of view of the experience gained during the response since the beginning of the full-scale invasion of the Russian Federation, the military attack, and the seizure of the Zaporizhzhia NPP at the beginning of March 2022.

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References

[1] Kyrylenko Y, Kameneva I, Popov O, Iatsyshyn A, Artemchuk V and Kovach V 2022 Actual Issues on Radiological Assessment for Events with Liquid Radioactive Materials Spills *Systems, Decision and Control in Energy III* ed Zaporozhets A (Cham: Springer International Publishing) pp 139–156 ISBN 978-3-030-87675-3 URL https://doi.org/10.1007/978-3-030-87675-3_8
[2] Popov O O, Kyrylenko Y O, Kameneva I P, Iatsyshyn A V, Iatsyshyn A V, Kovach V O, Artemchuk V O, Bliznyuk V N and Kiv A E 2022 *CTE Workshop Proceedings* **9** 306–322 URL https://doi.org/10.55056/cte.122
[3] Hoe S, McGinnity P, Charnock T, Gering F, Schou J, Lars H, Havskov Sørensen J, Andersson K G and Astrup P 2009 ARGOS Decision Support System for Emergency Management *12th International Congress of the International Radiation Protection Association - Buenos Aires, Argentina* (Argentine Radiation Protection Society) pp 1–10 URL https://backend.orbit.dtu.dk/ws/portalfiles/portal/3924948/Hoe_paper.pdf
[4] Ramsdell Jr J V, Athey G F and Rishelc J P 2013 RASCAL 4.3 User's Guide (Draft) URL https://www.nrc.gov/docs/ML1328/ML13281A701.pdf
[5] 2019 JRodos, Java based RODOS version URL https://resy5.ites.kit.edu/JRODOS/welcome.html
[6] Nuclear Energy Agency 2016 *Benchmarking of Fast-Running Software Tools Used to Model Releases During Nuclear Accidents* (Paris: OECD Publishing) URL https://www.oecd-nea.org/jcms/pl_19684/benchmarking-of-fast-running-software-tools-used-to-model-releases-during-nuclear-accidents
[7] Sørensen J H, Schönfeldt F, Sigg R, Pehrsson J, Lauritzen B, Bartnicki J, Klein H, Cordt Hoe S and Lindgren J 2018 *Benchmarking of Fast-Running Software Tools Used to Model Releases During Nuclear Accidents* (Nordic Nuclear Safety Research) URL https://backend.orbit.dtu.dk/ws/portalfiles/portal/143091609/Untitled.pdf
[8] Balashevska Y, Kyrylenko Y, Ivanov Z, Pecherytsa O and Shevchenko I 2022 *Nuclear and Radiation Safety* (2(94)) 26–35 URL https://doi.org/10.32918/nrs.2022.2(94).03
[9] Humphries L L, Beeny B A, Gelbard F, Louie D L and Phillips J 2017 *MELCOR Computer. Code Manuals. Vol. 1: Primer and Users' Guide. Version 2.2.9541* (Washington, DC: U.S. Nuclear Regulatory Commission) URL https://www.nrc.gov/docs/ML1704/ML17040A429.pdf
[10] Yatsyshyn T, Mykhailiuk Y, Liakh M, Mykhailiuk I, Savyk V and Dobrovolskyi I 2018 *Eastern-European Journal of Enterprise Technologies* **2**(10 (92)) 56–63 URL http://journals.uran.ua/eejet/article/view/126624
[11] Shkitsa L, Yatsyshyn T, Lyakh M and Sydorenko O 2020 *IOP Conference Series: Materials Science and Engineering* **749**(1) 012009 URL https://doi.org/10.1088/1757-899X/749/1/012009
[12] Soffer L, Burson S B, Ferrell C M, Lee R Y and Ridgely J N 1995 Accident Source Terms for Light-Water Nuclear Power Plants Final Report NUREG-1465 U.S. Nuclear Regulatory Commission URL https://www.nrc.gov/docs/ML0410/ML041040063.pdf
[13] International Atomic Energy Agency 1980 *Atmospheric Dispersion in Nuclear Power Plant Siting: A Safety Guide* (*Safety series* no 50-SG-S3) (Vienna: International Atomic Energy Agency) URL https://inis.iaea.org/collection/NCLCollectionStore/_Public/12/622/12622018.pdf
[14] Mukhopadhyay S, Baciu F, Saluja G, Segarra J and Albinet F 2018 Application of International Radiological Information Exchange (IRIX) standards for radiation monitoring data reporting *Radiation Detectors in Medicine, Industry, and National Security XIX* vol 10763 ed Grim G P, Furenlid L R, Barber H B and Koch J A International Society for Optics and Photonics (SPIE) p 1076308 URL https://doi.org/10.1117/12.2309380
[15] Cabinet of Ministers of Ukraine 2022 On approval of the Strategy of the integrated automated radiation monitoring system for the period until 2024 URL https://zakon.rada.gov.ua/laws/show/323-2022-%D1%80#Text
[16] Stein A F, Draxler R R, Rolph G D, Stunder B J B, Cohen M D and Ngan F 2015 *Bulletin of the American Meteorological Society* **96**(12) 2059 – 2077 URL https://doi.org/10.1175/BAMS-D-14-00110.1
[17] Rolph G, Stein A and Stunder B 2017 *Environmental Modelling & Software* **95** 210–228

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Short-term forecasting of electricity imbalances using artificial neural networks

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Short-term forecasting of electricity imbalances using artificial neural networks

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Abstract. Currently, the problem of improving results of short-term forecasting of electricity imbalances in the modern electricity market of Ukraine is a current problem. In order to solve this problem, two types of neural networks with recurrent layers LSTM and LSTNet were analyzed in this work. A comparison of the results of short-term forecasting of daily schedules of electricity imbalances using LSTM and LSTNet neural networks with vector autoregression model (VARMA) was carried out. Actual data of the balancing market were used for the research. Analysis of the results shows that the smallest forecast error was achieved using the LSTM artificial neural network architecture.

1. Introduction

Today, one of the important factors affecting the reliability and efficiency of the Integrated Power System (IPS) of Ukraine [1, 2] is the instability of electricity imbalances, which has been observed since the implementation of the new model of the wholesale electricity market [3].

Electricity imbalance – calculated in accordance with the rules of the electricity market [4] for each calculation period, the difference between the actual volumes of sale or consumption, import, export of electric energy of the party responsible for the balance, and the volumes of purchased and sold electric energy registered in accordance with the market rules. The overall electricity imbalances includes: the error of the forecast of the consumption of electric energy, the error of the forecast of the volumes of generation of renewable energy sources (RES) [5], the difference between the actual release of balancing service providers and the dispatch team, interruptions in power supply due to emergency situations in the power system.

At present, forecasting the value of overall electricity imbalances is a rather urgent task. In real time, the transmission system operator buys or sells the electricity needed to cover imbalances in the balancing market. According to the results of the balancing market sessions, the prices of imbalances are determined, according to which market participants get invoices for non-compliance with the declared volumes of electricity sales.

Access to prior information on electricity imbalance allows:

- the transmission system operator to improve the accuracy of creating the energy system operating mode. It also enables optimizing the balancing market and ancillary services market operations, thus increasing the reliability of the IPS of Ukraine functioning;
- market participants, including power companies, to determine their participation strategies in different market segments to reduce the cost of electricity [6];

- reducing the cost of imbalances for electricity suppliers, which has a positive impact on the retail electricity market and the prices of end consumers [7].

Previous developments to solve this problem were related to the study of autoregression models (ARIMA, ARIMAX, SARIMA, VARMA) [8]. Considering the widespread use of neural networks in various fields of application, it is appropriate to use this tool to solve the problem under study. Therefore, the purpose of this work is to develop and research models of artificial neural networks of deep learning for short-term forecasting of electrical energy imbalances of the power system and to compare the results with the results obtained using the VARMA vector autoregression model, which according to previous studies had the most accurate results.

2. Aim and methodology

Two types of neural networks with recurrent LSTM layers [9] and LSTNet [10] were built to predict electricity imbalances. After which two linear layers with hyperbolic tangent and sigmoid activation functions, respectively. Training was performed on 100 epochs and the ADAM optimization algorithm with a training step of 0.001.

The structure of the LSTM network is described using formulas (1-6) [11]. At the first stage, the information to be replaced is selected according to the conditions of the sigmoid layer (1). After that, the next layer determines the values to be updated (2) and builds a vector of values C'_t, which can be added to the state of the cell (3). Then the old state of the cell C_{t-1} is replaced by the new C_t according to equation (4). The last step is to calculate the source information using several filters (5, 6).

$$f_t = \sigma(W_f[h_{t-1}, x_t] + b_f), \tag{1}$$

$$i_t = \sigma(W_i[h_{t-1}, x_t] + b_i), \tag{2}$$

$$C' = tahn(W_c[h_{t-1}, x_t] + b_c), \tag{3}$$

$$C_t = f_t C_{t-1} + i_t C'_t, \tag{4}$$

$$o_t = \sigma(W_o[h_{t-1}, x_t] + b_o), \tag{5}$$

$$h_t = o_t tahn(C_t), \tag{6}$$

where σ is the activation function; W_f, W_i, W_c, W_o are weighting factors; b_f, b_i, b_c, b_o – shear coefficients; x_t – input data; h_{t-1}, h_t – forecast values; C'_t is the correction vector of the memory cell; C_t, C_{t-1} – state of the memory cell.

The memory vectors (C) and the LSTM output of the previous step (h) are initialized to zero values at each prediction step x_t. The vector C'_t represents a new version of the memory values, and the vectors f_i and i_i regulate the extent to which the memory vector is updated with new values. Due to the fact that the values of W_f, W_i and b_f, b_i are estimated during the learning process. The neural network regulates the update dynamics of C optimally from the point of view of minimizing the loss function. In addition, the presence of a memory vector makes it possible to reduce the effect of blurring or explosion of the gradient during the backpropagation of the error, while using a bypass connection, which smoothes the surface of the error of the neural network, significantly speeds up learning and allows to achieve a lower prediction error.

The built LSTNet network has the following components [10]:

1. *Convolutional.* The goal of an unconnected convolutional network is to extract short-term patterns in the temporal dimension.The output matrix simultaneously enters components 2 and 3.
2. *Recurrent.* Uses RELU as a hidden activation function. Result: hidden state for each timestamp.

3. *Recurrent-skip.* A repeating structure with temporal relationships to extend the temporal range of information, thus facilitating the optimization process. The structure of this layer is presented in the form of the following formulas:

$$r_t = \sigma(x_t W_{xr} + h_{t-p} W_{hr} + b_r), \tag{7}$$

$$u_t = \sigma(x_t W_{xu} + h_{t-p} W_{hu} + b_u), \tag{8}$$

$$c_t = RELU(x_t W_{xc} + r_t \otimes (h_{t-p} Whc) + b_c, \tag{9}$$

$$h_t = (1 - u_t) \otimes h_{t-p} + u_t \otimes c_t, \tag{10}$$

where p is the number of hidden cells;

4. *Temporal Attention Layer.* Learns the weighted sum of hidden representations at each window position of the input matrix. As a result, a concatenation of the context vector and the hidden representation of the last window together with a linear projection is obtained.
5. *Autoregression.* Breaks the final forecast into linear and non-linear components. The linear component solves the problem of local scaling, while the nonlinear one contains repeating patterns.

Both models are developed in the PyCharm environment using the Python programming language.

3. Results

Overall data include hourly volumes of positive and negative imbalances of the IPS of Ukraine for the period from 07/20/2020 to 07/16/2021 (a total of 8,784 values), training/test split is 90%/10%. The input vector includes 4 previous values; the forecasting horizon is 1 hour, the number of training epochs is 5000. The best prediction results were achieved with 20 hidden layer neurons. Data obtained from the official website of the National Energy Company Ukrenergo (balancing market and settlement of imbalances data). The test sample for comparison is 36 days. For comparison, the VARMA model was used.

Table 1 shows the average, maximum, and minimum relative errors for the test day of 07/20/2021 and the test sample as a whole, and table 2 shows the RMSE errors.

Table 1. Assessment of the accuracy of the studied models using MAPE, %.

Positive electricity imbalances						
	07/20/2021			Test sample		
	LSTNet	VARMA	LSTM	LSTNet	VARMA	LSTM
MAPE, %	46.95	40.86	20.73	132.78	140.84	66.25
δ, max, %	97.62	82.33	70.57	8253.21	5130.41	1789.01
δ,min, %	2.72	8.01	0.01	0.01	0.02	0.01
Negative electricity imbalances						
	07/20/2021			Test sample		
	LSTNet	VARMA	LSTM	LSTNet	VARMA	LSTM
MAPE, %	66.91	17.18	9.1	52.7	34.2	17.98
δ, max, %	78.62	35.55	23.05	221.43	322.16	279.56
δ,min, %	52.21	3.07	1.84	0.21	0.14	0.04

Figures 1-4 show daily values of MAPE, RMSE between actual ΔP_f and forecast values of electricity imbalances ΔP_p.

Table 2. Assessment of the accuracy of the studied models using RMSE, MW.

	Positive electricity imbalances			Negative electricity imbalances		
Model	LSTNet	VARMA	LSTM	LSTNet	VARMA	LSTM
07/20/2021	489.47	454.15	209.79	1015.72	342.87	163.74
Test sample	631.29	489.58	239.15	632.36	348.35	222.37

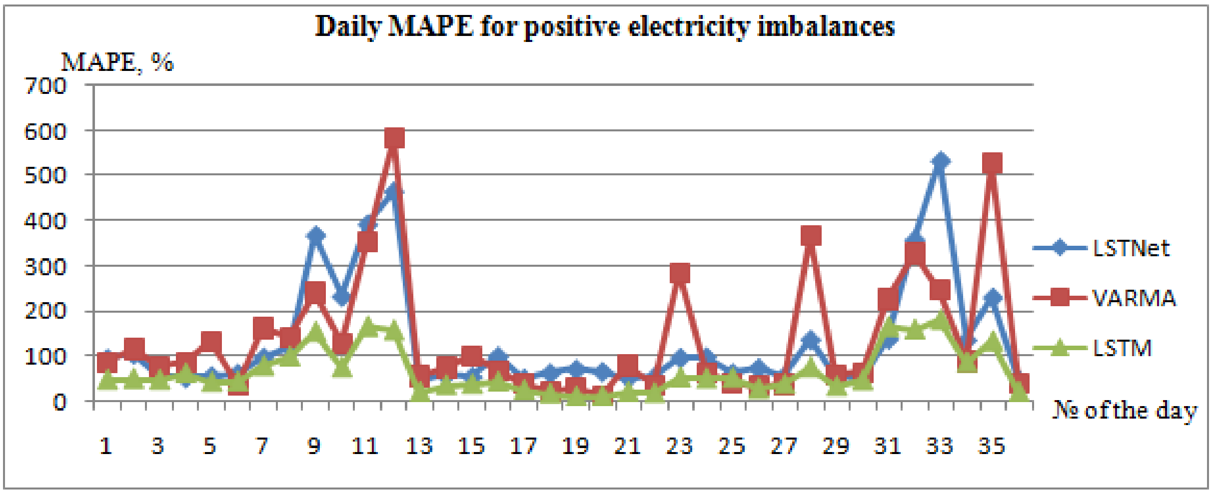

Figure 1. Daily graphs of MAPE values for positive electricity imbalances.

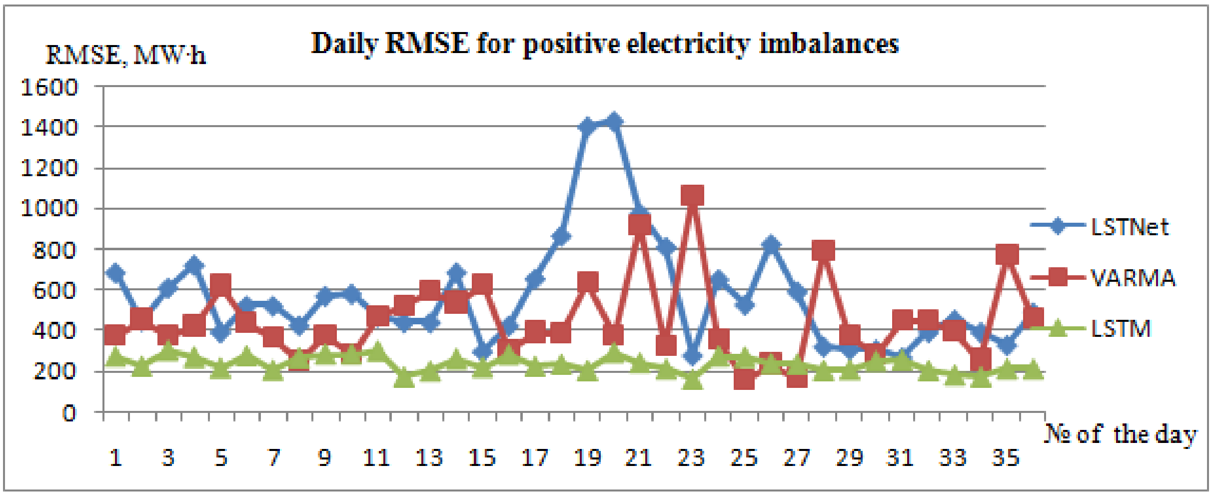

Figure 2. Daily graphs of RMSE values for positive electricity imbalances.

According to the data indicated in tables 1 and 2 and illustrated in figures 1-4, the most accurate forecasting results of both positive and negative electricity imbalances were obtained using the LSTM model. At the same time, the graphs of daily MAPE and RMSE errors for LSTM results have less pronounced local extrema, which indicates the preservation of the trend throughout the entire range of the test sample, i.e. greater stability of forecasting results. The results obtained with the LSTNet model are much worse: by 50% compared to the other models for positive imbalances and by 47% and 66% compared to VARMA and LSTNet, respectively, for negative imbalances.

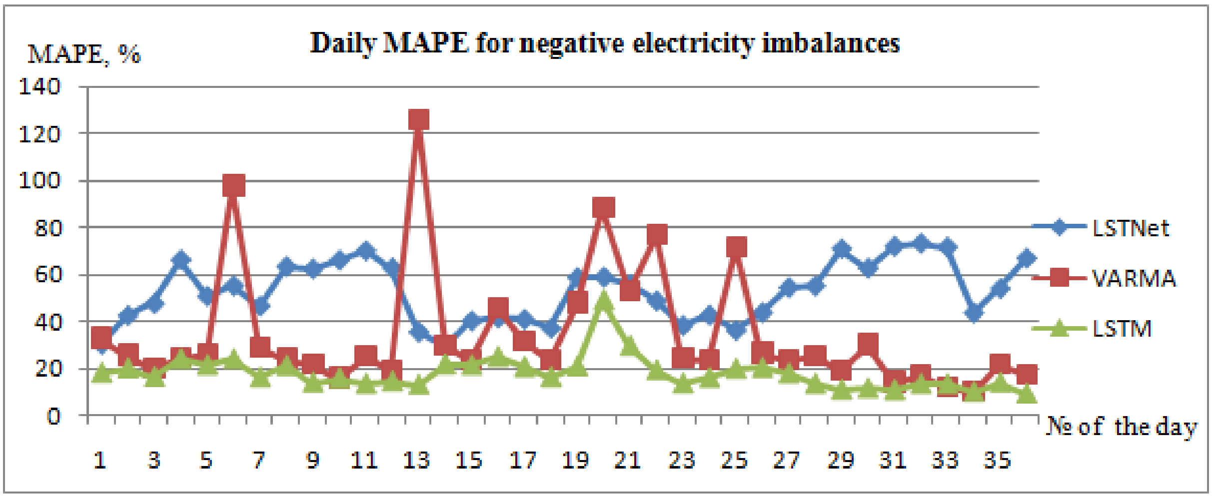

Figure 3. Daily graphs of MAPE values for negative electricity imbalances.

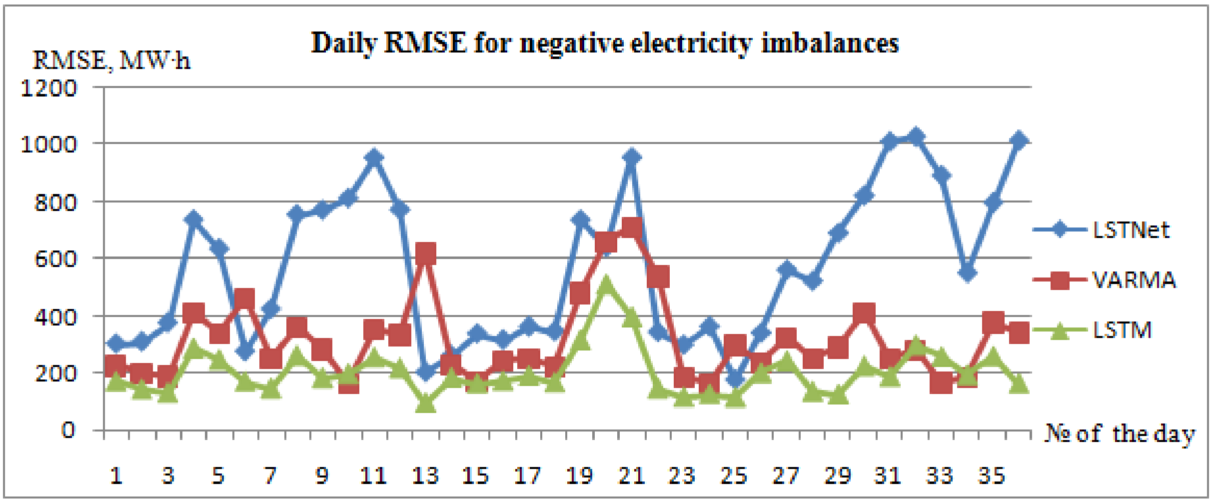

Figure 4. Daily graphs of RMSE values for negative power imbalances.

When forecasting positive electricity imbalances using the LSTM neural network, the errors of forecasting results increase slightly, with the exception of the third test day. This is due to the significant asymmetry of the distribution of positive imbalances. The use of the studied neural network for forecasting negative imbalances made it possible to reduce forecasting errors by 2÷5 times.

For example, figure 5 shows the values of electricity imbalances predicted using the built models, compared with the actual ones for 07/20/2021.

The analysis of the received forecasting results of the considered models shows the need to improve the method to include the impact of external factors on the value of electricity imbalances. Great asymmetry of imbalance data can be adverse in particular by finding other influencing factors and building a more flexible model of the connection between them. The significant asymmetry of the imbalance data suggests that data preparation can strongly influence the accuracy of forecasting results. Additional, some kind of mixture distribution models could be used for improving of forecast accuracy.

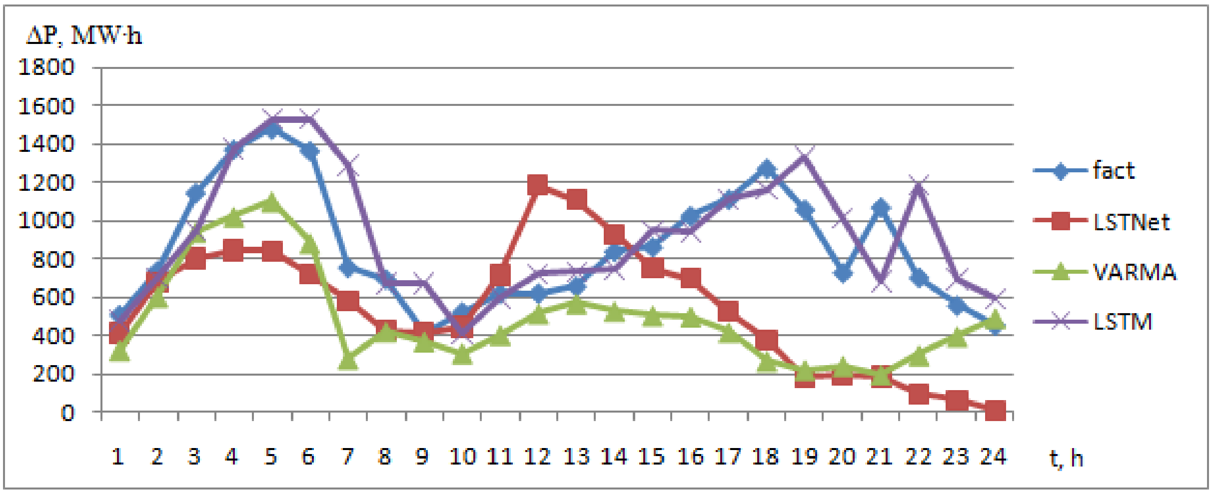

Figure 5. Graphs of electricity imbalance values, predicted using built models, compared with actual values for 07/20/2021.

4. Conclusions

The use of artificial neural networks made it possible to reduce the error of forecasting total electricity imbalances for different testing periods. LSTM shows the lowest values of MAPE forecasting error, for positive imbalances the daily forecast error is 20.73%, while for VARMA model the error is 40.86% and LSTM is 46.95%. When predicting negative imbalances, LSTM also has the lowest error value of 9.1%, compared to VARMA of 17.18% and LSTNet of 66.91%. The forecast on the entire data sample has significantly larger errors especially on the data of positive electricity imbalances, LSTM 66.25%, VARMA 140.84%, LSTNet 132.78% and for negative imbalance LSTM 17.98%, VARMA 34.2%, LSTMNet 52.7%. Therefore, the smallest error of forecasting results is achieved using an artificial neural network based on LSTM. In this way, the LSTM is the most effective method for imbalances forcasting in terms of flexibility and ability to model multivariate data, which essentially increases the effectiveness of forecasts.

The results of the conducted research prove the success of the proposed forecasting models and indicate the need for their further development taking into account additional factors.

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References

[1] Kyrylenko O V 2016 *Intelligent electrical networks: elements and modes* (Institute of Electrodynamics of the National Academy of Sciences of Ukraine)
[2] Verkhovna Rada of Ukraine 2017 On Electricity Market URL `https://zakon.rada.gov.ua/laws/show/2019-19?lang=en#Text`
[3] Spodniak P, Ollikka K and Honkapuro S 2019 The relevance of wholesale electricity market places: the Nordic case Working paper ESRI URL `http://aei.pitt.edu/id/eprint/102242`
[4] Natsionalna komisiia, shcho zdiisniuie derzhavne rehuliuvannia u sferakh enerhetyky ta komunalnykh posluh 2018 Pro zatverdzhennia Pravyl rynku [On Approval of Market Rules] URL `https://zakon.rada.gov.ua/laws/show/v0307874-18?lang=en#Text`
[5] Goodarzi S, Perera H N and Bunn D 2019 *Energy Policy* **134** 110827 ISSN 0301-4215 URL `https://doi.org/10.1016/j.enpol.2019.06.035`

[6] Ortner A and Totschnig G 2019 *Energy Strategy Reviews* **24** 111–120 ISSN 2211-467X URL `https://doi.org/10.1016/j.esr.2019.01.003`
[7] Golmohamadi H and Keypour R 2018 *Sustainable Energy, Grids and Networks* **13** 93–111 ISSN 2352-4677 URL `https://doi.org/10.1016/j.segan.2017.12.008`
[8] Blinov I, Miroshnyk V and Sychova V 2022 Comparison of models for short-term forecasting of electricity imbalances *2022 IEEE 8th International Conference on Energy Smart Systems (ESS)* pp 01–04 URL `https://doi.org/10.1109/ESS57819.2022.9969288`
[9] Thadajarassiri J, Hartvigsen T, Kong X and Rundensteiner E A 2021 *Proceedings of the AAAI Conference on Artificial Intelligence* **35**(11) 9859–9867 URL `https://doi.org/10.1609/aaai.v35i11.17185`
[10] Lai G, Chang W C, Yang Y and Liu H 2018 Modeling Long- and Short-Term Temporal Patterns with Deep Neural Networks (*Preprint* 1703.07015) URL `https://doi.org/10.48550/arXiv.1703.07015`
[11] Hochreiter S and Schmidhuber J 1997 *Neural Computation* **9**(8) 1735–1780 ISSN 0899-7667 URL `https://doi.org/10.1162/neco.1997.9.8.1735`

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SWOT analysis of electric transport and V2G implementation for power system sustainable development in the terms of Ukraine

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SWOT analysis of electric transport and V2G implementation for power system sustainable development in the terms of Ukraine

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Abstract. An analysis was carried out to examine the prospects for the integration of smart charging technologies, such as Vehicle-to-Grid (V2G), into the power system in Ukraine. The country is experiencing a growing concern regarding greenhouse gas emissions. The transport sector in Ukraine is one of the most energy-intensive sectors of the economy and contributes significantly to environmental degradation. The use of internal combustion engines in transport also increases the country's dependence on imported fuel due to the high demand for petroleum products. The integration of electric transport and smart charging technologies, particularly V2G, is seen as a critical solution with immense potential to mitigate climate change. V2G technology is becoming increasingly relevant as the world transitions towards a more sustainable energy future. V2G refers to the bi-directional flow of energy between electric vehicles (EVs) and the grid. With V2G, EVs can not only consume energy from the grid but also supply energy back to the grid during peak demand periods, helping to stabilize the grid and increase its resilience. Therefore, it is imperative to develop a stable policy to promote these technologies and compare the features of the policy of integrating electric vehicles and the energy system in Ukraine. A qualitative strategic planning methodology, Strengths, Weaknesses, Opportunities and Threats (SWOT) analysis, was used to evaluate the diverse measures and initiatives related to electric transport development and infrastructure while integrating them into the power system. This analysis identified problems associated with the impact of EV charging on the power system, such as the inability to provide increased energy needs or limiting the EV charging infrastructure load. However, a high percentage of renewable energy sources, increased social awareness of climate change, and reduced prices of electric vehicles could provide the necessary opportunities for developing electric transport in Ukraine.

1. Introduction

Today, the electrification of transport around the world is considered one of the key conditions for decarbonization for the implementation of the Paris Agreement and the implementation of nationally determined contributions, both in the countries of the world, Europe, in particular in Ukraine. The expansion of electric vehicles and renewable energy sources can greatly help in reducing the impact of climate change, but their effective integration is crucial. There is a widespread inclination to encourage electric vehicles by offering incentives at various levels, but a well-defined and consistent policy is necessary to foster the growth of electric mobility and related technologies. Of course, the widespread implementation, development and mass use of electric vehicles and its charging infrastructure should take place synchronously and in coordination with the corresponding transformation of the energy system.

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The purpose of this study is to review the current state and perform a comprehensive analysis of the prospects for the development of smart charging technologies for electric transport and their application in Ukraine. Also to consider the possibilities of creating new efficient energy transmission systems "electric transport – electric power industry", as well as to determine the main advantages and obstacles to the use of smart charging technologies in the electrical grids of Ukraine.

2. Modern state of the EV fleet and charging infrastructure development in Ukraine

In Ukraine, the transport industry, along with the energy sector, produces up to 28% of CO2 emissions. The volume of greenhouse emissions from the use of internal combustion engines (ICE), and with them the risks of global climate change and air pollution, make it expedient to widely introduce electric transport at all levels of transportation organization, and first of all it concerns the private use of electric vehicles and urban passenger transport (municipal fleet of electric buses, service road equipment, taxis, delivery services, etc.). This is also required by Ukraine's international environmental obligations.

While electrified transportation such as metros, electric trains, trolleybuses, and trams have been widely adopted for public transportation in many countries and are considered mature technologies, private electrified transportation like electric vehicles (EVs) have faced limited adoption in the past due to limitations in battery technology such as heavy weight, high price, short life, and long charging duration. However, recent breakthroughs in battery technology have made EVs a viable alternative to traditional gasoline vehicles, with fast declining prices and no local greenhouse gas emissions. EVs also boast high energy conversion efficiency compared to traditional vehicles, which suffer from inefficiencies associated with internal combustion engines. Many countries have implemented government programs that offer financial subsidies and tax exemptions to incentivize the purchase of EVs, while car manufacturers offer a range of EV models with varying specifications and prices, providing buyers with a wealth of options to suit their budgets [1].

According to the plans of the European Commission, by 2030, electric vehicles should make up half of all urban vehicles. It is expected that such a transition to an electric drive will significantly reduce emissions of noxious pollutants into the air and the level of acoustic pollution of the environment. According to the National Transport Strategy, Ukraine expects to completely switch to municipal transport with electric motors by 2030, completely replacing buses and fixed-route taxis.

Implementation of transport "greening" programs will allow Ukraine to significantly reduce greenhouse gas emissions, which is necessary to fulfill its obligations under the Paris Climate Agreement. According to the Ministry of Infrastructure of Ukraine as of 01.01.2022, there are about 10.2 million cars in the country. By replacing the Ukrainian motor transport system with an electric one, significant environmental results can be achieved.

The first electric cars in Ukraine were officially registered back in 2012. A noticeable increase in their number occurred in 2016 (1602 units against 470 units in 2015), which was associated with the beginning of the law on the abolition of duties on imports of electric vehicles from January 1, 2016. In 2021, 8,500 electric vehicles were registered in Ukraine. This is about 20% more than in 2020. The creation of a national infrastructure of charging stations will be an impetus not only for the spread of private electric transport, but also for municipal, and for the development of new services using electric vehicles, for example, in the field of logistics.

In 2022, the demand for electric cars in Ukraine increased 15 times due to the shortage provoked by military aggression and the rise in fuel prices. Due to the crisis in the fuel market in Ukraine, there was a rapid increase in demand for electric vehicles. Today, together with "hybrids", the number of electrified cars is more than 100 thousand (of which 42.3 thousand are

Table 1. Number of registered electric vehicles by regions of Ukraine.

#	Region of Ukraine	Number of electric vehicles Nov 1, 2021	Nov 1, 2022
1	Kyiv	7176	8965
2	Odessa region	4733	4871
3	Kyiv region	3730	3312
4	Kharkiv region	3178	3500
5	Dnipro region	2680	3836
6	Lviv region	2172	3246
7	Vinnytsia region	957	1656
8	Zaporizhia region	851	1241
9	Zhytomyr region	784	1305
10	Poltava region	637	1120
11	Rivne region	633	906
12	Khmelnytsky region.	518	1098
13	Chernivtsi region	515	917
14	Ternopil region	509	1035
15	Mykolaiv region	483	676
16	Ivano-Frankivsk region	481	803
17	Donetsk region	471	902
18	Cherkasy region	426	914
19	Volyn region	426	747
20	Transcarpathian region	410	832
21	Kherson region	248	409
22	Sumy region	223	447
23	Kropyvnytsky region	221	495
24	Chernihiv region	148	343
25	Lugansk region	50	254
26	AR of Crimea	2	24
	Ukraine (total)	32662	42289

pure electric vehicles, and more than 10 thousand were registered during 9 months of 2022).

As of November 1, 2022, the number of registered electric vehicles in Ukraine was 43854 units, and even more than 70,000 hybrids were registered in Ukraine. [1]. As for the distribution of electric vehicles by regions of Ukraine, as shown in table 1, the list is leaded by Kyiv, where as of November 1, 2022 there were 8965 registered EVs. And in the entire Kyiv region, together with Kyiv, their number reaches 12277 units or almost 28% of the total number in the country.

Main specific of the Ukrainian EV market is that the vast majority of it (up to 85%) are used electric vehicles from the USA and European countries. The most popular and widespread EV model in Ukraine is Nissan Leaf [1].

As there are more and more electric vehicles in Ukraine every month, this brings the development of charging infrastructure to the forefront. Note that for increasing the number of electric vehicles, it is critically important to develop a dense network of charging stations near the place of residence and work. Having the opportunity to charge near the place of residence, the consumer is more likely to choose an electric car when buying a car mobile. At the same time, it is economically unprofitable for businesses to build networks of charging stations without a sufficiently developed electric vehicle market in the short term [2].

According to [3], EVs can be charged at various locations such as large charging stations, street chargers, workplace chargers, and private home chargers. However, this new load, which requires a large amount of electric energy from the power system in a short time, can have detrimental effects on the distribution network if not managed properly. Consequently, utility companies will need to make significant infrastructure upgrades, which can be an economic burden. Therefore, to mitigate these negative effects, it is essential to conduct comprehensive studies [4] to understand and assess the characteristics of EVs' load and their probable effects on the electric power system, particularly the distribution networks. Furthermore, optimal integration techniques of EVs into the power grid should be developed and incorporated into the design, operation, and planning processes [5].

For charging stations and connectors, monitoring and accounting at the state level is not yet available, and with the outbreak of hostilities it is impossible physically. Data from open sources show that compared to 2020. the number of stations and charging ports (each station may have several connectors of different types) has decreased. So, if as of 1.01.2021 there were 11.5 thousand connection points (or connectors) in Ukraine, then as of 1.11.2021 – 7.8 thousand, the total number of charging stations – 3244. This is due to the fact that in 2021 Ukrainian the charging infrastructure market significantly changed its configuration – some operators merged, others left the market [6]. However, even so, at the beginning of 2022 the ratio of the number of electric vehicles to the number of connection points in Ukraine is 4.2. This is a high index, at the level of the best among European countries (the same index is, for example, in the Netherlands).

3. Charging strategies and technologies for electric vehicles

The rise in the number of electric vehicles has made them a significant component of the power supply system, both regionally and nationally. As electric vehicles continue to develop, the integration of smart grid technologies and electrical networks is being done with additional requirements and restrictions to effectively integrate them into the hybrid power supply system. In Ukraine, similar to other developed countries, there are opportunities for integrating electric vehicles into the electrical network to regulate the load of the power system. This integration process involves considering the charging modes of traction batteries of the cars [6].

The strategy is to charge vehicle batteries mainly during the minimum load of the power system, and during peak periods of time – to generate energy from the battery to the network. The mass use of electric vehicles in this mode will reduce the demand for electricity during peak periods, which, in turn, reduces the need for peak power plants and helps reduce harmful emissions, Since such generating sources are usually more environmentally friendly and efficient compared to power plants, which provide a constant (base) load. This task is relevant both for many European countries and for Ukraine.

Load shifting (pick shaving and valley filling) using the charging and discharging electric vehicles on the principle is similar to the system-wide one using pumped hydroelectric energy storages. To determine the regulating potential for the use of EVs in real conditions of power consumption, it is necessary to take into account the pattern of use of electric vehicles in a particular case of the operational load mode of the substation (vehicle mode in motion, charge/consumer mode, discharge/generator mode). Subject to the increasing fleet of electric vehicles and the effective use of V2G technology, it will be possible to take into account when designing the electrical network given source of active load. The most potential locations for charge-discharge stations in cities are parking lots in residential areas, near shopping and entertainment centers, etc.

In general, the creation of conditions for the spread of electric vehicles in Ukraine and the development of proper infrastructure has already begun at the state level, because the National Transport Strategy until 2030 and the developed appropriate action plan provide for such stimulation of the use of electric vehicles so that their fleet will make up to 70% of the total number of cars [6]. In general, in addition to the total number of charging points, the quality characteristics of charging are no less important – in other words, whether there are enough “fast” connectors in the country now. Currently, there are about 24% of “fast” connectors in Ukraine – each of them accounts for three “slow” ones. On the one hand, the European average in 2020 was lower than Ukrainian and amounted to 1 to 9 (”high-speed” charging accounted for 11.1% of the total). On the other hand, increasing the number of DC points is critical for accelerating the pace of electric mobility in Ukraine. After all, the capacity of batteries in new models of electric vehicles is constantly growing, having reached 70-80 kWh today. There are also already powerful electric vehicles with a battery capacity of about 100 kWh (for example, Tesla).

It’s important to mention that the infrastructure of charging stations is concentrated mainly in large cities, and on intercity routes the number of charging points is extremely limited. Therefore, it is believed that electric cars are most convenient for movement within the city. Conventional outlets are located both at gasoline stations and in roadside establishments, but it should be borne in mind that the time to recharge the car in this situation will be about 8-10 hours. In the case when there is an urgent need to urgently recharge during the day, it is necessary to look for high-speed charging, which is quite difficult.

Considering the experience of other nations, it can be contended that the demand for electric vehicles is predominantly influenced by factors such as the cost of electric vehicles, infrastructure development, and government incentive programs. Commercial freight carriers and private electric vehicles need more detailed programs to encourage, support and subsidies from the state. In addition, the mass use of electric transport will have an important social and environmental consequence – it will contribute to improving air quality in cities, which is one of the urgent threats in large cities of Ukraine. As for freight electric transport, its use may be the most economically feasible in large cities and agglomerations with a high population density, when it is not necessary to overcome very long distances.

The implementation of measures and initiatives to promote the development of the EV market has already begun in Ukraine:

– From January 1, 2022, the relevant laws came into force, providing for amendments to the Tax (Law No. 1660-IX [7], temporary exemption of electric vehicles and related goods from VAT taxation until 2026) and Customs (Law No. 1661-IX [8], temporary, until 2031, exemption from import duty) codes to stimulate the development of the electric transport industry in Ukraine.
– At the beginning of 2022, the Ministry of Infrastructure of Ukraine initiated the development of key changes in state building codes in terms of the placement of gas stations on the roads [9].
– In June 2022, “The Cabinet of Ministers approved the order developed by the Ministry of Energy “On the creation by the state enterprise “National Nuclear Energy Generating Company “Energoatom” of a network of high-speed automobile electric charging stations [10]. It is assumed that within two years Energoatom will create 120 automobile electric charging stations: 40 – high power (from 160 kW) and 80 – average power (from 60 kW). Charging stations will operate in regional centers and on the main highways of Ukraine.
– The Cabinet of Ministers has approved the introduction of “smart grids” in Ukraine until 2035 and its implementation action plan, following the proposal of the Ministry of Energy on October 14, 2022 [11]. This concept and action plan provide a framework for the implementation of modern technologies in the Ukrainian electric power industry, including during the reconstruction and restoration of energy infrastructure damaged by the Russian aggression. The restored energy sector of Ukraine is expected to embody modern energy ethical technologies and meet European energy efficiency standards. The concept aims to

gradually reduce electricity losses in networks, decrease CO2 emissions, increase investments in the modernization of power grids, and improve the quality and reliability of power supply for electricity consumers, which will directly affect electric transportation and optimize its interaction with the power system.

As a result of Action Plan implementation of this Concept by 2035, it is planned to reduce electricity losses in the power grids in Ukraine as a whole from 11.6% to 7.5% or by 6 billion kWh, which is equivalent to 3 million tons of burned coal at thermal power plants [12].

To facilitate the transition to electric transport, there are several actions that need to be taken, such as obtaining funds from international financial organizations to acquire electric vehicles for Ukrainian cities, creating a system to partially cover the costs of purchasing electric vehicles, and implementing various measures to enhance the environmental sustainability of transportation. For instance, introducing a road toll system that depends on the car's level of environmental standards, restructuring the technical condition monitoring system, and more.

4. The main characteristics of V2G

To prevent negative impacts on networks and energy systems, the European approach to developing infrastructure for electric vehicles is based on Smart Grid principles – intelligent power supply networks where charging stations, charging management systems, and electric vehicles can be controlled by energy companies to address the following challenges in power systems: enhancing network infrastructure efficiency, balancing peak loads, and developing appropriate network intellectual infrastructure. Smart networks are a necessary condition for optimizing power supply system operations and ensuring energy efficiency in the energy industry. Their application enables control and optimization of the charging process and the regulation of the energy consumed by vehicles based on network status during charging. To establish a consistent technical policy for solving these issues in Europe, a set of standards is being developed that regulates different aspects of charging station and device operation.

To date, several modifications of the concepts of smart networks for vehicles have been developed, depending on the number and type of active elements and their interaction and charging schemes. These include the concepts of V1G (Unidirectional Smart Charging, vehicle – network, unidirectional charging) and V2G (Vehicle-to-Grid, vehicle – network, bidirectional charging) and V2B/V2H/V2X (Vehicle-to-Building, vehicle – building/ Vehicle-to-Home, car – private house/ Vehicle-to-Everything, car – anything, bidirectional charging). The V1G system allows you to control the charging of electric vehicles in such a way that, if necessary, the charging power is increased or decreased. Unlike the V1G concept, the V2G and V2B/V2H/V2X concepts need several elements to work, such as a bidirectional charger, a communication protocol for the interaction between the charger and the car, a vehicle with all V2G capabilities, and an efficient system control (see figure 1).

Vehicle-to-grid (V2G) is a specific type of energy storage system that utilizes the batteries of electric vehicles (EVs) to store and release electricity to and from the power grid. V2G systems can provide a range of benefits, including supporting grid stability and reliability, reducing peak demand, and enabling the integration of renewable energy sources. V2G systems work by allowing EVs to charge when electricity is cheap and plentiful, and discharge their stored energy back to the grid when demand is high and electricity prices are elevated. This enables EV owners to earn revenue by selling their excess electricity back to the grid, while also helping to balance the grid and improve its overall efficiency.

While V2G systems are still in the early stages of development, they hold significant potential for the future of energy storage and grid stability. As more and more EVs are introduced onto the market and integrated into the grid, the potential for V2G systems to provide a significant source of flexible, reliable, and cost-effective energy storage will only continue to grow.

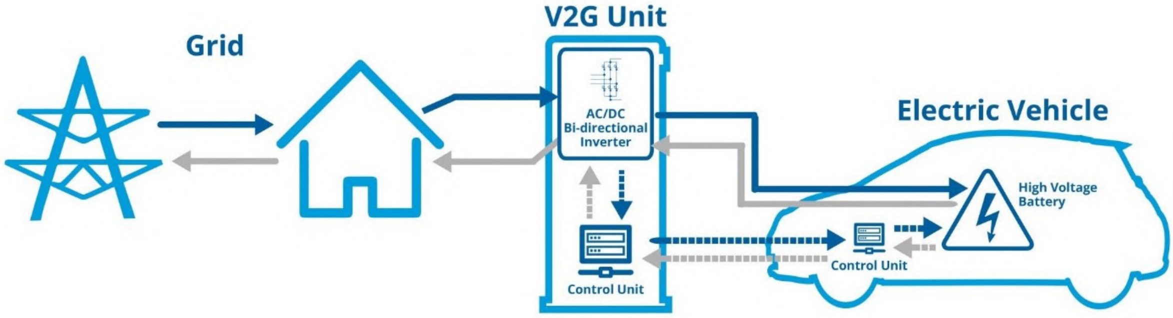

Figure 1. Scheme of bidirectional V2G charging [13].

Numerous research studies have been conducted to analyze the impact of uncontrolled electric vehicle (EV) charging on distribution networks. These studies take into consideration many uncertainties such as the start time of charging, charger power rating, charging location, EV battery capacity, EV battery state of charge (SoC) at the start of charging, penetration level, and the status of the distribution network [14]. These studies evaluated the impacts of uncontrolled EV charging on the distribution network's total power demand, transformer loading and lifespan, cable loading, voltage profile, power losses, voltage and current unbalance, and harmonics distortion. In addition, several studies have proposed potential solutions to integrate EVs optimally, such as delayed charging, smart charging, vehicle-to-grid (V2G) technology, vehicle-to-building (V2B) technology, and vehicle-to-home (V2H) technology [1,15–20]. These solutions could provide electrical services like frequency regulation, voltage regulation, and reactive power compensation, as well as peak shaving and valley filling, integrating renewable energy sources (RESs), spinning reserves, and improving power quality [1, 21]. With the continued growth of EVs, understanding their impact on the distribution network and exploring effective integration solutions is crucial for ensuring a stable and efficient energy system.

The process of charging electric vehicles can be divided into two broad categories (see figure 2): unidirectional and bidirectional charging. Unidirectional charging refers to the flow of energy from the grid to the electric vehicle, which can be either uncontrolled, delayed, or controlled charging. On the other hand, bidirectional charging refers to the flow of energy in both directions, allowing electric vehicles to not only draw power from the grid but also feed power back to the grid or to buildings and homes. This process is enabled by technologies like vehicle-to-grid (V2G), vehicle-to-building (V2B), and vehicle-to-home (V2H) systems.

Figure 3 provides a visual representation of the different charging and discharging methods impact on the power system. By implementing bidirectional charging solutions and other advanced technologies, the electric vehicle industry can work to minimize the negative impacts of uncontrolled charging on distribution networks while also providing a range of benefits to the power system and consumers alike.

The illustration depicted in figure 4 demonstrates how the profile of total power demand within the distribution system will be altered based on various charging and discharging methods. These methods include uncontrolled charging, delayed charging, controlled charging, as well as V2G, V2B, and V2H [22].

5. SWOT analysis of V2G implementation in Ukraine

The need to carry out a comprehensive assessment of all factors of influence of the external and internal environment to determine the possibilities and prospects for increasing electromobility in Ukraine is a condition for the development of an appropriate strategy, the basis for which is

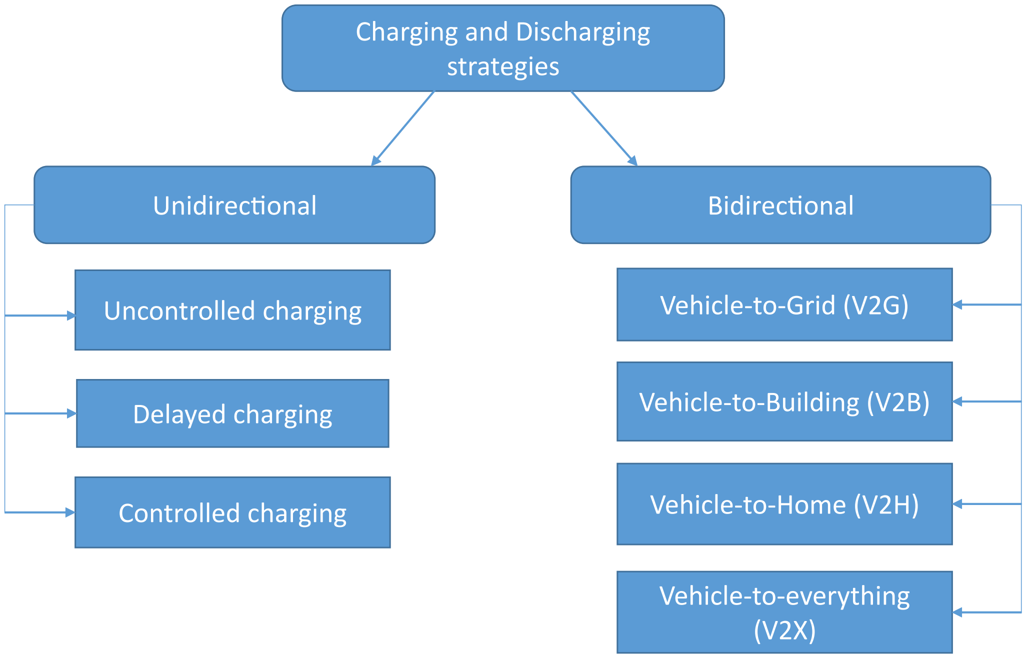

Figure 2. Different charging methods [22].

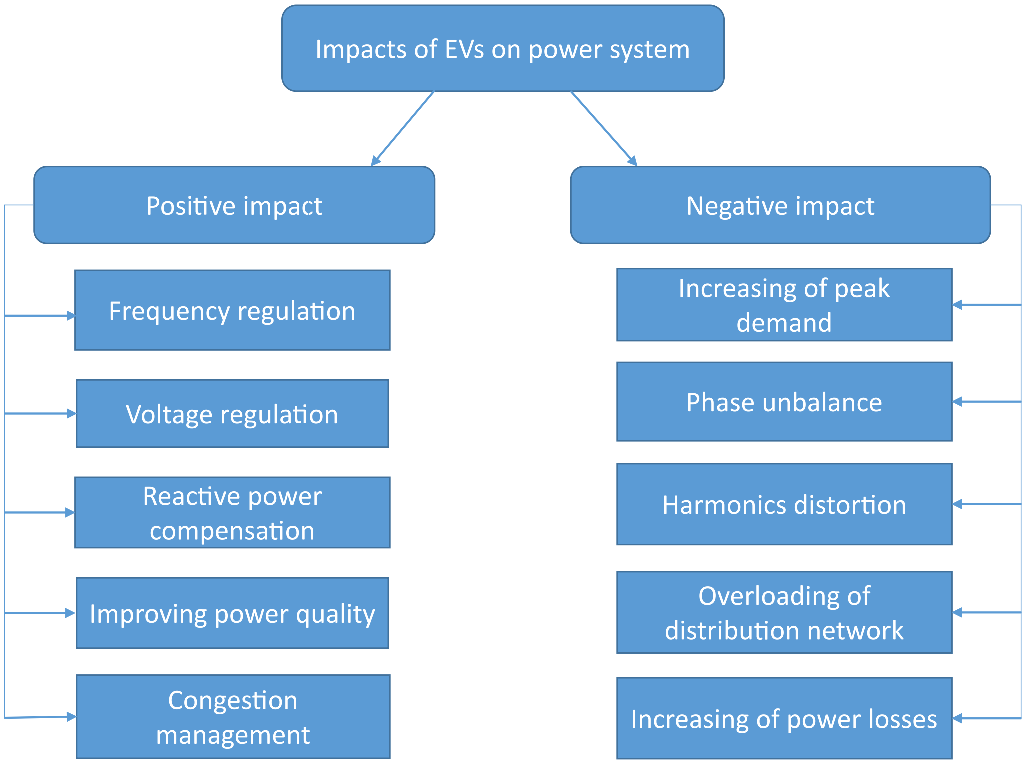

Figure 3. EVs charging impacts on power systems [22].

SWOT analysis [23].

The internal environment of the subject being analyzed is characterized by factors that can be considered as strengths (S) or weaknesses (W), which are influenced directly by the subject.

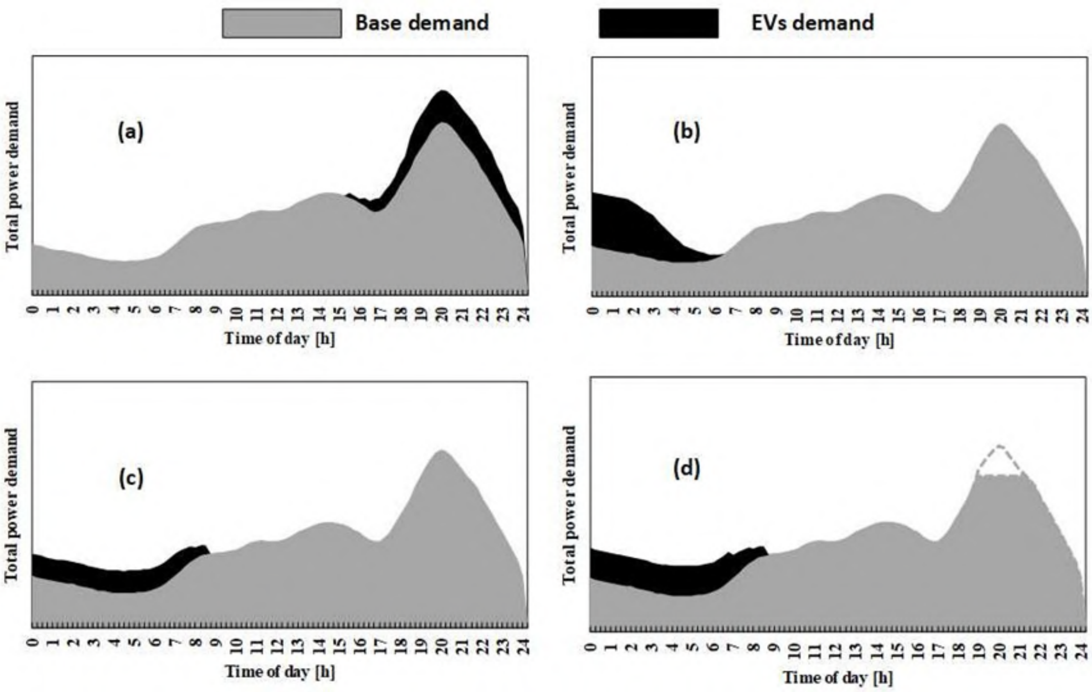

Figure 4. Power demand with uncontrolled (a), delayed (b), controlled (c), and V2G, V2B, V2H (d) charging methods [22].

On the other hand, the external environment is characterized by factors that are outside the subject's control and can be identified as opportunities (O) or threats (T) [23]. The advantages of the method: simplicity and the ability to spend small funds on its implementation, flexibility and the presence of many options, joint study of external and internal factors.

When considering the strengths of the development of electric transport and V2G technology, it was found that the use of electric vehicles instead of cars with internal combustion engines significantly reduces air pollution in cities. Traditional cars, even with high-quality petroleum fuels, emit a lot of pollutants. And electric cars are at the stage exploitation has no emissions. Emissions generated due to the generation of electricity are mostly left out of cities and sprayed to a significantly higher altitude, which is safe for public health.

Moreover, it was noted that V2G technology has the potential to lower the overall cost of owning electric vehicles and can be extended for localized use such as home energy storage and backup power in emergency situations. From the perspective of the grid operator, V2G provides a new resource for regulating and accumulating electricity, thereby offering a solution to the problem of fluctuations resulting from the increased use of renewable energy sources [2]. It also helps alleviate network congestion and obviates the need to modernize network infrastructure. Furthermore, V2G promotes a circular economy, enhances energy security, fosters a cleaner environment, and reduces noise pollution from vehicle engines. Consequently, the adoption of V2G technology and electric vehicles will trigger a significant shift in the way cities are structured, leading to substantial economic activity. For grid aggregators and operators, V2G technology creates new opportunities in the electricity sector, such as providing network balancing and renewable energy storage services in collaboration with utility companies, network operators, and consumers. Office and real estate owners can also benefit from V2G technology as it facilitates localized peak load reduction, load equalization, and balancing of electricity demand, ultimately reducing the total cost of electricity [2].

An electric engine with the calculation of losses during charging has an efficiency of about 85-90% of the electricity required from the network, which is 3 times higher than the efficiency of an internal combustion engine, which is about 30-35%. At the same time, if we take into account the losses in oil refining and the generation and transmission of electricity, then in terms of energy costs, these technologies are generally comparable. But for different countries and regions of the world, this balance is different depending on the structure of electricity generation. EVs through the driving specifics in cities are more efficient in terms of energy use than traditional cars.

Electricity is on average cheaper than gasoline and fluctuations in its price are insignificant compared to prices for motor fuel from oil. An electric car with the same characteristics will consume several times less fuel. As a result, depending on the country and energy source, the fuel costs of an electric car can be from 3 to 10 times lower. A car with an internal combustion engine has about 10,000 moving parts and components. In electric vehicles there are 1000-2000. The mechanics of parts of an electric car are much simpler and, accordingly, the wear of parts is less, and the cost of this is lower.

Also, an electric car is much easier to drive than a car with an internal combustion engine, due to one gear, a low center of gravity (due to the low location of the battery, which is usually located above the bottom of the car). Due to the absence of an engine in the front of the car, the electric car not only gives you additional space for the transport of goods, but also significantly increases the safety of the car.

Among the weaknesses is the cost of EV for its owner, which is still the biggest obstacle to its mass distribution. On average, the retail price of a middle-class car with an internal combustion engine is twice the price of an electric counterpart. In most models of electric vehicles, many parts are similar to cars with internal combustion engine. And the most expensive part of EV is a battery, which accounts for up to 40% of the final price of an electric car. EV battery cost decreasing will allow electric vehicles to become competitive in price. Furthermore, uncontrolled or haphazard charging of electric vehicles (EVs) can lead to a significant and uneven increase in the electrical load profile, particularly during the evening peak load. This is because most people tend to charge their EVs when they return home from work, resulting in an estimated increase of 8-10% in the evening peak load. This can pose a significant challenge for distribution networks. Moreover, the uneven geographical distribution of EVs and charging stations in cities and areas can also cause local substations to exceed their capacity, particularly in areas with a high concentration of EVs or charging stations [8].

Threats to the development of electric mobility are associated with the lack or limited access to the raw material base, including for the production of batteries, difficult political situation, strict national environmental standards and other regulatory requirements, restrictions on land use, insufficient development of related infrastructure, economic factors, etc. In addition, with the growing demand for electric vehicles requires new projects, and they are very expensive.

The results of fulfilled SWOT analysis are given in table 2.

After studying the successful experiences of countries that have implemented electric vehicles and V2G systems, it can be concluded that the demand for electric vehicles is heavily influenced by the cost for end-users, the development of necessary infrastructure, and government incentive programs. In order to encourage the use of electric vehicles in both commercial and private sectors, the government should provide detailed support programs and subsidies. Ukraine's implementation of transport "greening" programs would reduce greenhouse gas emissions and fulfill obligations under the Paris Climate Agreement. If Ukraine replaces 70% of its motor transport system with electric vehicles, it would achieve significant environmental results. However, the introduction of electric vehicles should be accompanied by infrastructure development, systems for interaction with the power system, and compliance with international environmental standards. Despite the higher initial cost of electric transport, its operating costs are expected to be lower in the long term, and as battery costs continue to decline, the share of

Table 2. Strengths, weaknesses, opportunities and threats of V2G implementation in Ukraine.

Strengths	Weaknesses
• Environmental friendliness, reduction of air pollution (especially in cities) • Sustainable growth of the electric car fleet in Ukraine, constant growth in demand • The efficiency of the electric motor is 85-90% (the efficiency of the internal combustion engine is 30-35%) • An electric car is more efficient in the urban cycle in terms of energy consumption • Electricity is much cheaper than fuel, characterized by lower price fluctuations • Favorable climatic conditions • Availability of existing electric transport and infrastructure • High share of private car ownership • Developed IT sector (smartphones, mobile applications, etc.) • Availability of a research base for the study of projects for the development of electric transport and infrastructure	• High price for new electric vehicles and the high price of replacing batteries • Low share of electric vehicles in the country's park compared to cars with internal combustion engines • Lack of additional incentives • 85% of electric vehicles are used, with partially degraded batteries • The need for daily charging, the need to determine the time and place • Relatively short mileage and additional reduction in power reserve in winter • Lack of a sufficient number of equipped parking areas for electric vehicles • Integration of electric vehicles with the power system is a complex long-term process that requires the development of rules and coordination of actions of all participants at all levels (charging infrastructure, energy market, renewable energy sources, energy supply companies, etc.) • Lack of own production of electric vehicles, batteries, V2G devices
Opportunities	**Threats**
• Reduction of CO2 emission (implementation of NVVP2) • Reducing the use of natural gas and petroleum products, reducing dependence on energy imports • Implementation and development of smart grid networks • The growing number of electric car models on the market • The growing popularity of electric vehicles • Implementation of the incentive and subsidy program • Use of electric transport as aconsumer-regulator of electrical load and as a distributed (mobile) storage of electricity • Increasing the flexibility of the power system • Use of batteries as a power reserve in emergency situations in the power system	• Probable rise in price of electricity • Further outflow of the solvent population without disabilities (due to war, economic downturn or lack of prospects for self-realization) • Large secondary market for more affordable cars with internal combustion engines • Charging electric vehicles directly depends on human life and increases the unevenness of the gene (especially in the evening peak zone) • Uncontrolled charging causes a number of negative effects in the power system (impact on grid stability and electricity quality) • Deterioration of distribution electrical networks • Accelerated battery degradation when participating in the V2G system (increase in charging-discharge cycles)

electric transport in the market is projected to increase.

Today there is an increase in demand for electric vehicles, but there are no economic and legal levers to stimulate the use of traction batteries as a maneuverable source, besides, V2G technology is not approved at the legislative level, there are no technical requirements for the relevant charging stations, and the network of standard charging stations is still underdeveloped [24].

The development of the infrastructure of powerful high-speed charging stations in Ukraine requires the modernization of the existing power grid and bringing it in line with European standards in order to ensure the ability of the power system to meet the needs of the charging infrastructure of electric vehicles, the number of which is constantly growing [25].

An action plan aimed at promoting electric vehicles in Ukraine should include several key measures. Firstly, it should encourage the innovative development of electric vehicles by stimulating their production in the country. Secondly, economic and other incentives should be introduced to promote the use of electric vehicles, including electric buses, bicycles, scooters, and other similar forms of transport in urban areas. Thirdly, a national network of high-speed charging stations for electric vehicles should be established along major international roads. Fourthly, incentives should be provided to carriers to reduce emissions of pollutants, greenhouse gases, and noise from vehicles. Fifthly, an interactive map should be created that identifies favorable locations for electric charging stations throughout Ukraine, including regional contexts. Sixthly, a monitoring system should be established to collect data on electricity consumption by charging stations to ensure the proper management and balancing of the energy system. Finally, there should be legislation determining the rights and obligations of operators of electric charging stations, the procedures and conditions for their participation in the electricity market, the rights and obligations of distribution system operators, suppliers, and consumers when using electric charging stations, as well as the procedure for connecting these stations to the electricity network.

In addition to all the above measures, it is also necessary to inform the public about state support for electric transport, in particular, timely and widespread information about benefits for electric vehicles and certain restrictions for cars with internal combustion engines. It is necessary to be widely informed about the advantages of electric vehicles in the media. For example, the fact that Tesla owners undergo a technical inspection remotely, which saves a lot of time, or that electric cars are much safer than cars with internal combustion engines, and this has been repeatedly proved by relevant tests. The policy of stimulating the widespread use of electric transport should be noted in all key development strategies of Ukraine: economic, energy, environmental, climate and infrastructure.

6. Conclusions

Using strategic planning methods, an analysis was conducted to examine the potential for implementing vehicle-to-grid (V2G) technology for electric transport and integrating it into the power system in Ukraine. The study showed that the transport sector in Ukraine has a significant impact on the environment, is energy-intensive, and contributes to the country's dependence on imported fuel. Electric vehicles (EV) and V2G smart charging technologies offer a promising solution to address climate change. Therefore, there is an urgent need to develop a stable policy to promote these technologies by comparing and determining the features of integrating EV and the power system in Ukraine.

A SWOT analysis was conducted to identify strengths, weaknesses, opportunities, and threats related to the development of EV and infrastructure integration with the power system. The study revealed potential problems related to the impact of EV charging on the power system, but opportunities such as a high percentage of renewable energy sources, public awareness of climate change, and lower prices for EVs can help promote their development in Ukraine.

The widespread adoption of EVs and related infrastructure, smart charging technologies, and adherence to international environmental standards can form a new sector of the economy and energy system in Ukraine (E-Mobility). The concept of developing electric transport in Ukraine should cover all types, including electric cars, minibuses, passenger buses, and trucks. Although EVs have a higher initial cost, their operating costs are significantly lower. As battery costs decrease in the future, the initial cost of EVs will be comparable to that of traditional vehicles, leading to an increase in their share in the country's total fleet.

In Ukraine, V2G technology is still in its early stages, with a limited number of pilot projects and trials currently underway. However, the potential benefits of V2G technology in Ukraine are significant, including the ability to reduce energy costs, improve grid stability and reliability, and support the integration of renewable energy sources. To fully realize the potential of V2G in Ukraine, there are several challenges that must be overcome. These challenges include a lack of infrastructure and investment, regulatory barriers, and the need for more research and development to optimize the technology. Overall, while there are significant challenges to overcome, the potential benefits of V2G in Ukraine are substantial, and efforts to develop smart technologies should continue to be one of the priorities for power sector.

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References

[1] AUTO-Consulting 2022 Yak zminylosia stavlennia vitchyznianykh avtomobilistiv do elektromobiliv cherez vidkliuchennia elektryky [How the attitude of domestic motorists to electric cars has changed due to power outages] URL https://autoconsulting.ua/article.php?sid=52536

[2] Natkha O 2020 Elektromobili chy zariadna infrastruktura: shcho pervynne [Electric cars or charging infrastructure: which comes first] URL https://ua-energy.org/uk/posts/elektromobili-chy-zariadna-infrastruktura-shcho-pervynne

[3] Knez M, Zevnik G K and Obrecht M 2019 *Renewable and Sustainable Energy Reviews* **109** 284–293 URL https://doi.org/10.1016/j.rser.2019.04.013

[4] Dubey A and Santoso S 2015 *IEEE Access* **3** 1871–1893 URL https://doi.org/10.1109/access.2015.2476996

[5] García-Villalobos J, Zamora I, San Martín J, Asensio F J and Aperribay V 2014 *Renewable and Sustainable Energy Reviews* **38** 717–731 URL https://doi.org/10.1016/j.rser.2014.07.040

[6] Kytina M 2021 Elektromobiliv bilshe – zariadok menshe: shcho vidbuvaietsia v Ukraini iz zariadnoiu infrastrukturoiu [More electric cars, less charging: what's happening with charging infrastructure in Ukraine] URL https://auto.rbc.ua/ukr/show/zaryadnaya-infrastruktura-1637906584.html

[7] Verkhovna Rada of Ukraine 2021 Pro vnesennia zmin do rozdilu XX "Perekhidni polozhennia" Podatkovoho kodeksu Ukrainy shchodo stymuliuvannia rozvytku haluzi ekolohichnoho transportu v Ukraini [On Amendments to Section XX "Transitional Provisions" of the Tax Code of Ukraine regarding the Stimulation of the Development of Ecological Transport in Ukraine] URL https://zakon.rada.gov.ua/laws/show/1660-20#Text

[8] Verkhovna Rada of Ukraine 2021 Pro vnesennia zminy do punktu 4 rozdilu XXI "Prykintsevi ta perekhidni polozhennia" Mytnoho kodeksu Ukrainy shchodo stymuliuvannia rozvytku haluzi ekolohichnoho transportu v Ukraini [On Amendments to Paragraph 4 of Section XXI "Final and Transitional Provisions" of the Customs Code of Ukraine regarding the promotion of the development of ecological transport in Ukraine] URL https://zakon.rada.gov.ua/laws/show/1661-20#Text

[9] Government portal of Ukraine 2020 Maiemo stymuliuvaty vykorystannia elektromobiliv v Ukraini ta stvoryty nalezhnu infrastrukturu, - Vladyslav Kryklii [We need to stimulate the use of electric vehicles in Ukraine and create the proper infrastructure, - Vladyslav Krykliy] URL https://cutt.ly/gwdg0zY6

[10] Verkhovna Rada of Ukraine 2022 Pro skhvalennia Kontseptsii vprovadzhennia "rozumnykh merezh" v Ukraini do 2035 roku [On Approval of the Concept for the Implementation of Smart Grids in Ukraine by 2035] URL https://zakon.rada.gov.ua/laws/show/908-2022-%D1%80#Text

[11] Haus B and Mercorelli P 2020 *IEEE Transactions on Vehicular Technology* **69**(2) 1452–1463 URL https://doi.org/10.1109/tvt.2019.2959720
[12] Nour M, Said S M, Ali A and Farkas C 2019 Smart Charging of Electric Vehicles According to Electricity Price *2019 International Conference on Innovative Trends in Computer Engineering (ITCE)* (IEEE) URL https://doi.org/10.1109/itce.2019.8646425
[13] Douris C 2017 Electric Vehicle-To-Grid Services Can Feed, Stabilize Power Supply URL https://www.forbes.com/sites/constancedouris/2017/12/18/electric-vehicle-to-grid-services-can-feed-stabilize-power-supply/
[14] Nafisi H 2019 *International Journal of Ambient Energy* **42**(7) 744–750 URL https://doi.org/10.1080/01430750.2018.1563816
[15] Nour M, Ramadan H, Ali A and Farkas C 2018 Impacts of plug-in electric vehicles charging on low voltage distribution network *2018 International Conference on Innovative Trends in Computer Engineering (ITCE)* pp 357–362 URL https://doi.org/10.1109/ITCE.2018.8316650
[16] Tong X, Ma Q, Tang K, Liu H and Li C 2019 *The Journal of Engineering* **2019**(16) 2658–2662 URL https://doi.org/10.1049/joe.2018.8906
[17] Nour M, Ali A and Farkas C 2019 Mitigation of Electric Vehicles Charging Impacts on Distribution Network with Photovoltaic Generation *2019 International Conference on Innovative Trends in Computer Engineering (ITCE)* (IEEE) URL https://doi.org/10.1109/ITCE.2019.8646632
[18] Ul-Haq A, Azhar M, Mahmoud Y, Perwaiz A and Al-Ammar E 2017 *Energies* **10**(9) 1351 URL https://doi.org/10.3390/en10091351
[19] Leou R C, Teng J H, Lu H J, Lan B R, Chen H T, Hsieh T Y and Su C L 2018 *IET Generation, Transmission & Distribution* **12**(11) 2725–2734 URL https://doi.org/10.1049/iet-gtd.2018.0112
[20] Yong J Y, Ramachandaramurthy V K, Tan K M and Mithulananthan N 2015 *Renewable and Sustainable Energy Reviews* **49** 365–385 ISSN 1364-0321 URL https://doi.org/10.1016/j.rser.2015.04.130
[21] Hota A R, Juvvanapudi M and Bajpai P 2014 *Renewable and Sustainable Energy Reviews* **30** 217–229 ISSN 1364-0321 URL https://doi.org/10.1016/j.rser.2013.10.008
[22] Nour M, Chaves-Ávila J P, Magdy G and Sánchez-Miralles Á 2020 *Energies* **13**(18) 4675 URL https://doi.org/10.3390/en13184675
[23] Podolchak N I 2012 *Stratehichnyi menedzhment* (Lviv: Vydavnytstvo Lvivskoi politekhniky)
[24] Kostenko A P 2022 *System Research in Energy* **2022**(1) 62–71 URL https://doi.org/10.15407/srenergy2022.01.062
[25] Kyrylenko O V, Pavlovsky V V and Blinov I V 2022 *Technical Electrodynamics* **2022**(5) 59–66 URL https://doi.org/10.15407/techned2022.05.059

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High-quality education for better sustainability and resiliency

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Abstract. The world meets poly crises in climate, pandemic, energy, food, human rights, and migration; hot and cold wars have come in Europe and other regions. The scope of the tasks becomes unprecedented, and their complexity demands high-level skill sets and teaching culture. Education moves into epicentres of the fight for better sustainability and resilience. The United National Sustainable Development Goals Four (SDG4) supposes allocating and diligently using several trillion US dollars for the next decades. The ambitious goals drive the educational system to be at a decent level regarding outcome and process. Saving gratitude to functions of a fundamental human right, a public good, gender equality, and an absolute right to education for all, the author urges that high-quality education is the priority because it will help society to cope with a new level of challenges and even existential threats the climate-like. The article describes the methodology and the importance of soft-hard skills for teaching and learning. The secondary-based sources research illustrates practical results regarding the educational process. The Triple Bottom Line principle (Planet, Profit, People) encompasses many disciplines engaging the main aspects of sustainability and resiliency and climate change for the university curricula in a coherent way. The article considers future trends in high education and case studies connected with the European Green Deal, environmental, social, and governance (ESG) reporting and practical aspects of Green Growth and De-Growth Theory. The Quality of Education reflects the regulator's requirements and social and personal expectations. Life-long learning becomes a norm. The authors consider university products, processes and platforms through the lens of future trends, threats and opportunities. In times of turbulence, the results obtained through students' upskilling and reskilling programs should fit the demands of new jobs, technologies, and financial mechanisms.

1. Introduction

The world meets poly crises in many domains: climate, pandemic, energy, food, human rights, and migration; hot and cold wars have come in Europe and are filtering through other regions. The scope of the tasks becomes unprecedented, and its complexity entails high-level skill sets to meet demands.

Sustainability allows pursuing long-term value and raising resilience to turn disruptions into opportunities. Education is the universal recipe for operating in advance and when challenges emerge.

So, the high quality of education moves into epicentres of the fight for better sustainability and resilience. The United National Sustainable Development Goals Four (SDG4) supposes allocating worldwide and diligently using several trillion US dollars for the next decades. The ambitious goals drive the educational system to be at a decent level regarding outcomes and flexibility of teaching and learning processes.

The EU Green and Tweens transition [1] and Paris Agreement [2] have initiated a paradigm shift from short-term to long-term values to ensure the internalisation of environmental, social, and governance (ESG) *externalities*. The EU Council approved the Corporate Sustainability Reporting Directive (CSRD), marking it as an expansion of the corporate EU [3]. The latter impacts universities and academia to teach the board members and executives managers because non-financial ESG reporting has become mandatory for European companies. The same trend also prevails for the world. Under new regulations, large companies will include reporting on climate-related risks and the impact of activities on climate change. Mandatory disclosure comprises direct and indirect greenhouse gas (GHG) emissions, GHG reduction targets and how the companies plan to implement these goals. Enforcement of the new rule implies sufficient time to implement the new disclosure requirements. It shapes newly sizable requests for universities and academia to create new courses.

United Nations Sustainable Development Goal (SDG) [4] addresses $SDG4$ as "Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all". That is a heart for the achievement of all seventeen SDGs. $SDG4$ articulates gratitude to functions of a fundamental human right, a public good, gender equality, and an absolute right to education for all. During the poly-crisis, the author believes that high-quality education is the priority because it will help society cope with new challenges and even existential threats the climate-like.

The hard truth is that the world can slide into a new period of war, poverty and disease. The Russian aggression forced countries like Germany to increase their defence budget significantly, and countries like Sweden introduced military service again. Education, healthcare, and social workers funding will move to tanks, missiles and cybersecurity [5]. However, even today, most transformative digital companies rapidly scale educational platforms reaching millions of learners, companies, and institutions. Life-long learning becomes an avenue to find new roles, skills, and jobs in a time of uncertainty. Graduates and children need to access high-quality education in their lifecycle terms. These two drivers fuel further development.

Society, stakeholders, and students must obtain a spectrum of general, specific, and 'ready to use' knowledge across targeted domains: energy, climate, security, industries, transport, buildings, agro, and healthcare. For example, energy contributes heavily to achieving many SDGs. So, raising energy engineering awareness inside curricula becomes a priority. The same ambition applies to science and innovations, policy and industry retention. Capital flow follows government regulation and market signals to pursue the opportunity to achieve growth and scale. Whatever happens, people, enterprises, and institutions need to grow new leaders, employees and researchers. People deserve to get equal access to education for all.

2. Methodology

The system and critical thinking, the theory of changes, and social research methods are the methodologies of this work. Provided the social nature of the researched subject, the secondary sources [6] became the distinguish sources for practical examples. The system thinking approach includes classifying objects, elements, links, and tasks as a holistic system by thinking over models [7]. Critical thinking supports open-minded mode [8] and allows researchers to recognise fakes, biases, half-true statements and narratives, and omitted facts. On the one hand, students can learn this discipline in the framework of high-quality studies and training, and its systematic application helps decision-makers to justify the subjects from many angles, on the other hand. For planning and development, the theory of change (ToC) [9] gives an outcome-based concept directed to complete the list of actions with the following evaluation of strategic individual projects and programs. The ToC presented the results of inputs, activities (short-, medium-, and long-term changes), outputs, outcomes, and intended impacts. The author uses secondary data analysis as long as the primary public data collects sufficient foundation to process high-quality education for better sustainability and resiliency.

Following Elkington, the author of the Triple Bottom Line principle (Planet, People, Profit), this article does not consider the De-Growth theory as "a communistic narrative" [10]. Indeed, there are resource limits for growth in the world [11] Otherwise, some researchers believe that Green Growth for free does not exist [12] because there is no such thing as a "free lunch". Under some circumstances, brown growth, or sustainability and resilience necessities, could temporarily leave Green Growth and climate agenda behind. For example, it is compulsory during wars. Typically, "the quality of education" (QE) comprises the education system's characteristics, reflecting the degree of compliance of accurate educational results achieved with regulatory requirements and social and personal expectations. In this article, the concept of "the quality of education" refers to both the result (outcomes) and the process (offline, online, hybrid) of education. The SDG4 functions' QE' as a fundamental human right, a public good, gender equality, and an absolute right to get education for all have taken for granted.

Data works for those familiar with model thinking [13] G.E. Pukhov Institute for Modelling in Energy Engineering of NAS of Ukraine carry on a pioneer study of digital resiliency. Among others, the institute is simulating the future of critical infrastructure regarding the Internet and the decentralised electricity market of Ukraine. Behind these studies stand serious mathematics and topology methods [14]. It brings additional opportunities to spread models and methodology across national infrastructure for long-term planning. Such plans can touch not only energy and utilities but, correspondingly, ICT, finance, healthcare, food, water, transport, defence, databases, and manufacturing domains. The ultimate objective aims at increasing the digital resiliency of critical infrastructure. Digital resiliency is "the ability to anticipate, withstand, recover from, and adapt to adverse conditions, stresses, attacks, or compromises on systems that use or are enabled by cyber resources" [15].

Culture, philosophy, and individual mindset usually impact the context of sustainability and resilience in our perceptions. For example, the difference between resilience and anti-fragility defines differently depending on the consideration method. Resilience increases the system's stability, and anti-fragility targets it to become a different system. From more traditional standpoints, the subjects of resiliency and anti-fragility can overlap or possibly, be congruent. Culture and Philosophy help to translate ethical dilemmas related to the tsunami growth of artificial intelligence (AI), robots, the Internet of things(IoT), digital technology and uncrewed-driving cars and facilities. That is not an accident that the position of Chief Philosophical Officer (CPO) is a subject of discussion in the specialised literature [16]. Is the golden age of philosophy coming again? Behind granular theories and project management guidance, researchers will see better the big picture of technological systems, jobs and education.

3. Future skills: main trends

3.1. Future skills, educational process and life-long learning

The Council of Europe Charter on Education for Democratic Citizenship and Human Rights Education has adopted that all learners acquire the knowledge and skills needed to promote sustainable development according to $SDG4.7$, $Education for sustainable development$ and $global citizenship$ [17]. $UNESCO$ highlighted the educational system, teaching and learning processes with outcomes as core elements [18]. The educational system, the policy, institutions, regulation, monitoring, improvements, and resources mobilising complies with $SDG4$. Observing plenty of literature entails the "no consensus" on the definition of quality education, and the latter largely depends on the context. With the Sustainability, Resiliency, and Climate Change context, the quality of education addresses both the results, particularly to meet future skills for the labour market, and the education process.

Online education increased share compared with offline and hybrid education. It happened because of $COVID-19$ and the blossoming of technology: ICT – Information and communication technology, EFA – Education for all, DE – Distance education. An educational institution can capture this opportunity to teach and learn or sometimes in remote mode with the implication of the e-learning process [19]. When we talk about distance learning, we should indicate what we mean. Distance learning involves a particular program, for example, Moodle, with all the necessary theory, practical tasks, control or test tasks, instructions, and other materials. That allows students to learn the material, work out practical cases and check the material's absorption level. Unlike distance, someone began to call remote training "as not in the classroom", which is not entirely accurate from a methodological point of view. Indeed, personal contacts are hard during the study through Zoom, Google Meet, Teams, and Webex. However, remote or distance learning allows students from different countries to study the subjects and obtain knowledge.

For technology adoption and automation to create productivity growth in Europe, there are three main prognoses where the educational system and the governments have a role to play: 1. Reskilling and upskilling human capital of the people already in their working lives (more than 50% of the total number); 2. Tens of millions of new jobs; for instance, 80 million people have to retrain in heat pump installation. It is a small part of the clean tech sector. 3. Over 50 million jobs could be automated by 2030. There will be a critical need to create new and teach different jobs [20].

Most jobs requiring green skills represent annual growth within 8-20% and are fresh and new: Sustainability Manager, Wind Turbine Technician, Solar Consultant, Ecologist, Environmental Health and Safety Specialist, Compliance Manager, Facilities Manager, and Technical Sales Representative. Below are some examples of trends-evoking skills and prospective jobs to cover up-skill and re-skill deliverables for the trends. The topic of jobs gained and lost resulting in the technology adoption for the years ahead is always hot. Automatisation and AI will have a tremendous impact. Universities have enough work to maintain the transition from the current status of the workforce to the future architecture of skills aligned with the labour markets. Quite logical that new technologies will displace relatively easy automated workers. Occupations that require a combination of hard and soft skills can seek new employees, given that the last jobs for automation are full of social and emotional skills, creativity, and cognitive capacity.

3.2. Sustainability, resilience, and climate change

Poly-crises and climate change have initiated a paradigm shift from short-term to long-term values where non-financial externalities, environmental, social, and governance(ESG) are the unseparated part of any consideration, products, and practices. So, educational institutions can provide adaptation in their curriculums by measuring performance and return, managing operations, marketing, organisational leadership, incentives and governance [3] and dealing with ESG issues foreseen familiarity with bio-diversity, human rights, supply chain equality, diversity and inclusion, climate change mitigation and adaptation [21]. As never before, climate change literacy and numeracy come to the fore. A combination of hard and soft skills allows learners to achieve cross-disciplinary objectives, which causes a necessity to obtain emotional and social intelligence skills [22].

Developing sustainability, resiliency, and climate change initiatives with governmental support through ESG policy and blended finance will also impact the new technology and critical market infrastructure. That is an argument for why education has to re-educate the ESG teams. For instance, the solar PV industry creates an additional 1 300 jobs for each gigawatt capacity just for the manufacturing stage [23]. The culture of lectors and professors increases the ranking of the institutions. Academic honesty and an ability to create new approaches and absorb existing knowledge and International best practices save stakeholder time to achieve better sustainability and resiliency.

3.3. COVID-19: great reset

COVID-19 has taught society to raise awareness of automation and the urgent need to accelerate related processes towards more tech and digital. In 2016, some academics concluded that up to 86% of restaurants, 75% of retail and 59% of entertainment jobs could be automated by 2035 [24] incumbent understanding of digitalisation becomes much more profound and broader. The following justifications regarding trends and cyber-attacks confirm an increasing role of digitalisation, cybersecurity, AI and immersing technology awareness.

Here are selected business trends in 2023 and further years (selected) [25]: 1. E-commerce growth persists post-pandemic; 2. $5G$ vastly improves data collection and AI capabilities; 3. Employees actively seek out remote and hybrid work; 4. Companies focus on sustainability; 5. Businesses experiment with immersive technologies like augmented reality (AR), virtual reality (VR), and mixed reality (MR); 6. More people become freelancers and entrepreneurs; 7. Innovation impacts last-mile delivery – nearly all businesses suffered supply chain disruptions due to the pandemic; 8. Customers save costs through AI.

An increasing number of cyber-attacks on critical infrastructure, financial, healthcare, and other networked systems negatively impact ESG, environment and social justice. Regulators and the insurance industry cannot tackle cybersecurity. The World Economic Forum [26] suggests including cyber risks in ESG strategies because of three foundations: 1. It presents a threat to value, particularly intangible assets; 2. It presents a threat to society; 3. Insurance cannot mitigate the risk indefinitely.

3.4. Ukraine, rebuilding – a trillion-dollar challenges

Now post-war future of Ukraine is widely discussed in the world. There are plenty of project estimations that it takes hundreds of thousands to even one trillion dollars to rebuild and rehabilitate the country. The private-public-partnership (PPP) is one of the most practical ways for upcoming rebuilding [27].

Rebuilding Ukraine could be the biggest Western project since Marshall Plan after $WW2$ [28]. It looks like the venture with a long story of massively failed projects: big budgets, huge promises, big teams, and plans reminded documentation of fantasy. Do not forget to mitigate the risks of corruption. Ukraine and the West do not have the experience to manage these vast opportunities and risks. McGrath urges that learning is the only way out of the uncertainty trap.

Following her adopted advice, she did it together with Flyvjberg and Gardner [29]: 1. Work backwards, starting with the goal; 2. Understand odds. Most big ambitious projects fail; 3. Plan slow, act fast; 4. Lego blocks. Small steps best build big ones; 5. Build the Team; 6. Master the unknown unknowns. Dispel the myth that exact projects are unique; 7. Know that the most significant risk is the human factor.

Standardisation and regulation barriers frequently stand behind advanced practices, so the revision is urgent, especially for industries with a complicated and safety-significant supply chain [30]. It encompasses several technical, scientific, legal, financial, and military areas, professional education and study. The rebuilding plan for Ukraine should cover regulations much beyond the current status.

Not only Ukraine itself but any country and their unions don't have the traction to cope with the magnitude of the rebuilding objective Ukraine is facing. Behind this new chapter in Ukrainian history should stand advanced technologies and innovations such as new generation internet, modelling, AI, IoT, 5/6G, Data, Quantum computing and censoring, ML, Dl, blockchain, clouds, and others. Like any sizable or significant transformations, project leaders matchmake academic, educational, and industry within and across countries. In advance, therefore, the government and universities need to look for teachers, researchers, and experts from industry, academia, and entrepreneurs. That is a relatively frugal solution and sustainable for any country, even though it takes time.

3.5. R&D internalisation, energy system, and new generation of Internet
When Ukraine is now more into maintaining the energy system operational, the EU countries address thoughts to market design for fulfilling three objectives: fairness, optimal investment, and optimal operation. [31]. It brings us to analyse some specific concepts:

Overcentralisation vs decentralisation. A decentralised market model for the resilient energy system comes to the fore for scientists and practitioners because of overcentralised physical energy structure doesn't fit emergency and market needs. The war is a visible driver to zoom into decentralising the electricity, water, and power market models. With the introduction of new technologies, such as wind, storage, smart grids, solar, and prosumerism concept, these new becomes an integral part of a complex energy system, its elements, and interwoven grids.

Digital Resiliency and New Generation Internet. Producers and suppliers can exchange their roles, which gives impetus for prosumerism and smart-response and metering development. That is why digitalisation heavily impacts all processes in the electricity and affiliated markets. The flow of reliable data, in combination with nascent next-generation internet technologies, represents the start of the transition to a new norm.

R&D internalisation. Due to nations and companies having unequal access to new technologies, developed counties set up different incentives and institutional frameworks. The US Defence Advanced Research Projects Agency (DARPA) [32] is one of the best role models. Another excellent example is Canada's innovation ecosystem where the Mitacs (Monreal) [33] is a catalysing force with focus areas and application domains fitted to future challenges. Mitacs can engage the expertise of universities, academia, and thousands of experts in Canada and worldwide. What is unique, they deal with big names, such as Ericsson, Cisco, and Oracle. The technological giant Ericsson, for example, launched in Canada's Quantum hub to support research [34]. They also onboard people in the team after up-skilling and re-skilling them using the study's 5G and virtual reality technologies. This practice helps the company to design new processes, methodologies, technologies, and new ways of collaboration.

4. High-quality education: case-study
4.1. Disciplines and process
The effective incorporation of sustainability and resiliency concepts and principles through all levels of the education system may pose particular challenges. The global market only for green energy will exceed \$1.1 tn by 2027. Demand for jobs only for sustainability managers will rise 8% annually until 2030, with up to 14 Mio jobs in 2030 [35]. Such hectic demand for educational service couples with the multidisciplinary nature of the sustainability, resiliency and climate change issues. So, regulators, universities and academia also need to adjust their up-skilling and re-spilling program and standards for specific disciplines, generations, and demography. Targeted competencies find their reflection in the scientific and methodological materials of the courses. Moreover, as a rule, competencies do not depend on the form of training: full-time, distance learning or mixed form. The exception is social skills, which require different approaches to their formation in various processes and platforms for learning.

When it comes to distance learning, the regulatory acts sometimes are not aimed at improving the educational process. In particular, it concerns reducing the pedagogical burden of distance learning. It is always happened, for example, in Ukraine before the war. The factors of optimisation of distance learning include the increased role of visualisation of material (theoretical material presented in the form of video lectures, as well as some practical tasks using video and audio files). The pandemic time shows it is unrealistic to insist on this with a minimum of teaching hours, only relying on the teacher's enthusiasm.

Universities play a central role in developing knowledge, including many domains, such as engineering, sciences, architecture, law, management, economics, sociology and even philosophy. They share knowledge and deal with academia, research institutions, government agencies, civil society and the private sector to ensure better employability of students. The extensive range of disciplines and backgrounds requires different approaches, including the main aspects of sustainability, resiliency and climate change, in the curricula coherently.

4.2. Distinctive curricula

The distinct requirements arise from the need to address sustainability, resiliency, and climate change. In today's educational landscape, teachers play multifaceted roles, serving as mentors, interpreters of knowledge, and bridges between generations. Their influence significantly impacts students' personalities and values. Therefore, it is crucial for educational curricula to incorporate specific and general knowledge tailored to students' needs, encompassing the following aspects:

1. *Multidisciplinary and system thinking*: A modern education should equip students with the ability to prioritize effectively. In times of peace, addressing climate change might take precedence, while during periods of turmoil, focusing on the sustainability and resilience of territories or sectors becomes crucial. Universities now emphasize teaching critical thinking and problem-solving skills, as well as the theory of change. Learning is indispensable to navigate uncertainty in situations involving mega projects and potential risks, as evidenced by the case of Ukraine.
2. *Integrating culture and philosophy*: The culture of teaching plays a pivotal role in delivering quality education. Teachers not only impart knowledge but also mold students' personalities, instilling values and fostering critical thinking. Academic integrity is gaining prominence, with a growing emphasis on originality and the ability to express one's ideas. Ensuring academic honesty from the early stages of education fosters respect for others' work.
3. *Developing a comprehensive set of skills*: Training programs need to adapt to the evolving demands of the professional world. This includes equipping students with both hard and soft skills, understanding taxonomy, and cultivating effective stakeholder relations. Striking a balance between theory and practice becomes essential. Specific skills in handling data (primary, secondary, and treaty), sustainable finance, innovative financial mechanisms, and ESG (environmental, social, governance) policies are crucial. Additionally, cybersecurity literacy and numeracy are necessary to manage cyber risks effectively. Equipping students with game-changer and mega-project skills, legal knowledge for public-private partnerships, and financial and technological tools for strategic planning and risk management is essential for their future success.

Incorporating these elements into education enables students to be well-prepared for the complexities of a rapidly changing world and to contribute positively to society's sustainable development.

4.3. Digital learning and EdTech platforms

The software makes learning more modern and efficient. The pandemic boosted digital and remote learning all around the world. As never before, the Digital Learning and Edtech industry provides equal opportunity and access to education for all. About 150 best EdTech companies [36] reached over three billion people and generated approximately USD 20 billion in revenue. The Digital Learning market is steadily growing by double digits annually.

Zooms, Teams, Webex, Viber, Facebook, and others became survival facilities for most institutions and companies. The author got a first-hand experience as a lecturer at the university. Here are some pros and cons. In particular, Moodle allows a unified presentation of theoretical material, including video lectures, practical, test tasks, and methodical recommendations, allowing students to navigate more quickly in the material. Moodle presents an ability to process large amounts of information, including test surveys, and place and check different types of work. Professional Zoom allows the host to divide students into small groups, which is evident during the discussion.

Meanwhile, the teacher can visit subgroups and check how the task goes. Overall, both tools help to engage active methods of training. By conducting classes through Zoom, the lecture encounters some advantages and disadvantages. The advantages include good visibility and audibility of the material, which does not constantly occur in the old-school audience. The Zoom drawbacks are the difficulty obtaining quick feedback and the limited ability to lead a lecture-discussion.

All major universities and companies with good financial positions have advanced EdTech platforms. Let us consider the state of the arts regarding EdTech platforms and Digital Learning. For example, the Yale School of Management offers offline study and two online programs: delivered live and cohort-based asynchronous [37]. The Yale School delivers teaching and research dealing with two online certified learning providers 2U/GetSmarter's learning platform offers 24/7 assistance to fit into a busy lifestyle. Short courses typically last for six-eight weeks in a cohort-asynchronous manner to prepare future leaders. ExecOnline is helpful when the school conducts three or six weeks of courses integrated with interactive programmes with short videos.

The top 150 EdTech companies focus on three major sectors: Life-Long Learning, Higher Ed, and K-12 by leveraging technology to increase access and affordability of quality and outcomes for learners. Re-skilling is an adult consumer learning, as the Life-Long Learning workforce represents 42% of all categories. In parallel, EdTech leaders have achieved the highest Return on Education (RoE), having extraordinary growth and traction. Edtech companies include publicly listed digital learning companies Grammarly, Coursera, 2U/GetSmarter, Grand Canyon Education, Kahoot, Docebo, Upwork, ExecOnline, Afya, and Arco [38]. In other words, universities have a wide choice to pick out what is better for their students and teachers, and it is not easy because of financial reasons and technological items.

4.4. Case study

Some observers have noted signs of distrust in the levels of university qualifications. Ernst & Young, for example, did not find evidence that university success correlates with work performance achievement. It gives life to skills-based or competency-based hiring practices. Many large companies with extensive human resources (HR) departments can assess applicants for their skills in-house. Small and medium-sized companies, however, still rely on qualifications as they do not have the resources to conduct assessments in-house. Public-sector employers and regulated professions are obliged by law to value qualifications [39].

What can help universities and academia to deliver sustainability and resiliency education and increase the level of trust and quality for diplomas and certificates? The sustainability and resiliency skill requirements are highly innovative. The Hart Research Associates found that the critical skills that distinguish innovators most from non-innovators are creativity, critical thinking, and problem-solving. Linguistic patterns as "come up with new ideas and solutions", the "willingness to question ideas", the "ability to present ideas in the audience", "alertness to opportunities", "analytical thinking", and "ability to coordinate activities"; and the "ability to acquire new knowledge", these are actual signs labelled required non-routine skills [40].

Some selected examples illustrated were moving in the primary, secondary, and tertiary educational processes to cope with climate crises and for better sustainability and resiliency. The Harvard Business School [3] has excellent traction as it is also fair for Columbia Business School [41]. The Black Rock has 'In-House' learning and development programmes [42].

Here are the results of our secondary research regarding the expectation of bachelor students regarding education and the future labour market. The Institute of Sociological Research of the Kyiv National Economic University named after Badym Hetman conducted the primary research in 2022 from 25.01 to 05.04. For successful quality assurance in line with the Bologna Process, the institute used an internal and QA system based on proven ICT, online, and mobile technologies:

(i) *Offline study.* 79.3% of respondents consider themselves satisfied with studying at university students. If chosen by composition, then the most Satisfied with the role of the teacher: defence teacher and student – 86.2%, the level of teaching – 72.4%.The level of satisfaction with the theoretical (58.6%) and practical (55.1%) secondary training. Worst is the situation with students' social and everyday life and assessment of international relations university (35.4%). Yes, for social infrastructure, 34.5% of respondents were satisfied with the logistics use – 41.3% leisure visits, and 44.8% were students. The results demonstrate that the university's ranking largely depends on the culture of lectors and professors.

(ii) *Online learning.* When considering this synchronous (Zoom, Team, Meet) e-mode or classroom activity (Moodle and others), respondents equally distributed such difficulties, respectively, 51.7% and 55.2%. Answers indicate significant difficulties tackling hardware, computer tools, and communications equipment, and the software – programs themselves are not a subject of complaints. Such difficulties stem from poor communication because of the types of equipment, low bandwidth, or even zero access to the Internet. Such problems relate to financial or technical obstacles for the students and teachers working from their homes. Now the situation has turned from bad to worse because of the Russian invasion of Ukraine. Teaching and learning are almost impossible because of additional mobile connection problems.

(iii) *Hybrid learning.* Even though the respondents put first place the negative consequences of the "lack of constant access to the Internet", 34.5% answered emphasised an inconvenient distance learning platform (Moodle, MS Office 365) – 34.%. That is quite likely that the platform does not support the issue. Insufficient training of students and lectures on how to use the platform is the case. 20.7% of the respondents confirmed this opinion.

(iv) Interestingly, 79.3% of the students agreed that receiving current and controlled tasks is more convenient. Plus, 75.8% rated having more free time as a positive factor because they got additional time avoiding time-extensive travelling to the university, the road and inconvenient schedules (the availability of free time between classes, even an hour and a half), or long breaks between classes. The students are happy to get more flexibility for productive activity and at home, which indicates a necessity to better instruct the platform's users from the teaching and learning side.

5. Conclusions

The quality of education reflects the regulator's requirements and social and personal expectations, a fundamental human right to education as a public good based on inclusivity and gender equality. Quality refers to the content and results obtained through students' up-skilling and re-skilling. The process breaks down into offline, online, and hybrid. Universities should set up and hone their educational products, processes and platforms by covering the following items:

(i) These disciplines' sustainability, resiliency, and climate have come to the global cutting edge in different orders. The culture of teaching and teaching is paramount for the quality of education, and it impacts all human activities, including policy, law, technology, finance, industries, and a mindset of critical and system thinking and problem-solving. That is why universities must adopt curricula via environmental, social, and governance(ESG) considerations together with hard and soft disciplines.

(ii) Prioritisation. In a time of peace, climate change is the priority. In wartime or turbulence, sustainability or resilience can be a more important priority in the short and medium-term perspective. Under some circumstances, even brown technologies based on fossil fuel and other necessities could temporarily leave Green development behind. For example, during wars or severe energy and food problems, middle and low-income countries sometimes cannot find another choice to survive.

(iii) Wars and Education. The funding for 'classical' education in a time of peace inevitably succumbs to military and cybersecurity arrangements. The curricula, unfortunately, witness an increasing role of the military. However, ongoing digitalisation, cybersecurity, AI and immersing technology awareness still leave the opportunity for further development for denoted professions.

(iv) Demand for New Jobs in the labour market: Reskilling and upskilling human capital are urgent because about 50% of the total work will change; It embraces tens of millions of new jobs; for instance, 80 million people have to retrain only for heat pumps. Over 50 million jobs could be automated by 2030.

(v) The proposal to Teach the New Jobs: educational institutions should provide adaptation in their curriculums regarding transformation for better sustainability and resiliency, measuring performance and return, incentives and green governance.

(vi) Quality process of Education. Options: 1. The up-skill and re-skill programme for students and specialists. Environmental, social, and governance(ESG) are the unseparated part of any consideration today; 2. Online, Offline, Hybrid. Online education increased share compared with offline and hybrid education. Within online, universities have a choice to deliver live or cohort-based programmes. Eventually, educational institutions can capture teaching with the implication of market fit.

(vii) Educational Platforms. For successful quality assurance, conducting research and delivering teaching in line with the Bologna Process, the universities and academia need to have a system based on proven communication technology and access to online and mobile technologies. There are many current proposals from EdTech Platforms where the cost of licences and technical support are the main bottleneck.

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References

[1] 2022 European Climate Law URL https://climate.ec.europa.eu/eu-action/european-green-deal/european-climate-law_en
[2] 2022 Paris Agreement URL https://climate.ec.europa.eu/eu-action/international-action-climate-change/climate-negotiations/paris-agreement_en
[3] Galdón C, Haanaes K, Halbheer D, Howard-Grenville J, Goulven K L, Rosenberg M, Tufano P and Whitelaw A 2022 *Harvard Business Review* ISSN 0017-8012 URL https://hbr.org/2022/02/business-schools-must-do-more-to-address-the-climate-crisis
[4] United Nations 2022 Sustainable Development Goals URL https://www.un.org/en/sustainable-development-goals
[5] 2022 ► About – Implementation of Education Quality Assurance system via cooperation of University-Business-Government in HEIs URL http://web.elth.ucv.ro/eduqas/about/
[6] Bryman A, Bell E, Reck J and Fields J 2021 *Social Research Methods* (Oxford University Press) ISBN 9780190853662

[7] Sterman J D 2000 *Business Dynamics: Systems Thinking and Modeling for a Complex World* (McGraw-Hill Education) URL https://sa85c2e82e126a3ae.jimcontent.com/download/version/1360070105/module/6264585279/name/%E6%96%87%E5%AD%97BUSINESS_DYNAMICS.pdf
[8] Van Damme D and Zahner D (eds) 2022 *Does Higher Education Teach Students to Think Critically?* (Paris: OECD Publishing) URL https://doi.org/10.1787/cc9fa6aa-en
[9] United Nations Development Assistance Framework 2017 UNDAF companion guidance: Theory of change URL https://unsdg.un.org/resources/theory-change-undaf-companion-guidance
[10] Hogan F 2022 Roar Interviews Environmentalist and Author John Elkington URL https://roarnews.co.uk/2022/roar-interviews-environmentalist-and-author-john-elkington/
[11] Raworth K 2017 *Doughnut Economics: Seven Ways to Think Like a 21st-Century Economist* (Chelsea Green Publishing) ISBN 9781603586740
[12] Triodos Investment Management 2022 Outlook 2023 - Resilience new solutions URL https://www.triodos-im.com/articles/2022/long-term-outlook---resilience-and-new-solutions
[13] Page S E 2018 *The Model Thinker: What You Need to Know to Make Data Work for You* (Basic Books)
[14] Zubok V Y and Mokhor V V 2021 *Data Recording, Storage & Processing* **23**(1) 48–58 ISSN 1560-9189 URL https://doi.org/10.35681/1560-9189.2021.23.1.235297
[15] Ross R, Pillitteri V, Graubart R, Bodeau D and McQuaid R 2021 Developing Cyber-Resilient Systems: A Systems Security Engineering Approach NIST Special Publication 800-160, Volume 2 Revision 1 National Institute of Standards and Technology Gaithersburg, MD URL https://doi.org/10.6028/NIST.SP.800-160v2r1
[16] Walsh T 2018 *2062: The World that AI Made* (Carlton: La Trobe University Press) ISBN 978-1-76064-051-4
[17] Council of Europe 2020 4.7 Education for sustainable development and global citizenship URL https://www.coe.int/en/web/education/4.7-education-for-sustainable-development-and-global-citizenship
[18] Global Education Monitoring Report Team 2004 *Education for all: the quality imperative; EFA global monitoring report, 2005* (Paris: UNESCO Publishing) URL https://unesdoc.unesco.org/ark:/48223/pf0000137333
[19] Emanuel A and Gelche N 2020 Distance Learning: A Viable Option *Quality Education* ed Leal Filho W, Azul A M, Brandli L, Özuyar P G and Wall T (Cham: Springer International Publishing) pp 174–184 ISBN 978-3-319-95870-5 URL https://doi.org/10.1007/978-3-319-95870-5_16
[20] Allas T 2022 The future of work and reskilling in Europe. URL https://www.mckinsey.com/featured-insights/lifting-europes-ambition/videos-and-podcasts/the-future-of-work-and-reskilling-in-europe
[21] Smith P 2022 The digitalising of procurement in 2023 – vital, growing and confusing URL https://www.cips.org/supply-management/opinion/2022/decenber/the-digitalising-of-procurement-in-2023-vital-growing-and-confusing/
[22] Goleman D 2005 *Emotional Intelligence: Why It Can Matter More Than IQ* 10th ed (New York: Random House Publishing Group) ISBN 978-0-553-38371-3 URL https://www.academia.edu/37329006
[23] 2022 Special Report on Solar PV Global Supply Chains Tech. rep. International Energy Agency URL https://www.iea.org/reports/solar-pv-global-supply-chains
[24] Schwab K and Malleret T 2020 *COVID-19: The Great Reset* (Cologny/Geneva: World Economic Forum) ISBN 978-2-940631-12-4 URL http://reparti.free.fr/schwab2020.pdf
[25] Howarth J 2023 9 Top Business Trends (2023 & 2024) URL https://explodingtopics.com/blog/business-trends
[26] Sarnek A and Dolan C 2022 Cybersecurity is an environmental, social and governance issue. Here's why URL https://www.weforum.org/agenda/2022/03/three-reasons-why-cybersecurity-is-a-critical-component-of-esg/
[27] Maksymenko M and Mushka R 2022 Role of PPP in Rebuilding Ukraine URL https://ukrainianlawfirms.com/reviews/infrastructure/
[28] McGrath R 2022 Rebuilding Ukraine: Huge opportunity, huge risks? URL https://www.ritamcgrath.com/sparks/2022/12/rebuilding-ukraine-huge-opportunity-huge-risks/
[29] Flyvbjerg B and Gardner D 2023 *How Big Things Get Done: The Surprising Factors That Determine the Fate of Every Project, from Home Renovations to Space Exploration and Everything In Between* (Signal) ISBN 9780771098437
[30] Prazian M 2023 *Nuclear and Radiation Safety* (1(97)) 67–70 URL https://nuclear-journal.com/index.php/journal/article/view/1000
[31] Zachmann G and Heusaff C 2023 Phased European Union electricity market reform URL https://www.bruegel.org/policy-brief/phased-european-union-electricity-market-reform
[32] Mazzucato M 2021 *Mission Economy: A Moonshot Guide to Changing Capitalism Hardcover – March 23, 2021* (New York: Harper Business) ISBN 978-0-06-304623-8

[33] Mitacs 2021 Innovation Futures: From Idea to Impact: Mitacs Strategic Plan 2021 URL https://www.mitacs.ca/sites/default/files/mitacs_strategic_plan_2021.pdf
[34] George K 2022 A digital path to sustainability URL https://www.mckinsey.com/capabilities/operations/our-insights/a-digital-path-to-sustainability
[35] Haanaes K 2022 Bridging the sustainability skills gap URL https://www.imd.org/ibyimd/sustainability/bridging-the-sustainability-skills-gap/
[36] Global Silicon Valley 2023 GSV 150 URL https://www.asugsvsummit.com/gsv-150
[37] Yale School of Management 2023 Executive Education URL https://som.yale.edu/executive-education
[38] Argo A 2022 GSV Edtech 150 — The Most Transformational Growth Companies in Digital Learning URL https://medium.com/gsv-ventures/gsv-edtech-150-the-most-transformational-growth-companies-in-digital-learning-39b6252048e7
[39] OECD 2022 *Education at a Glance 2022: OECD Indicators* (Paris: OECD Publishing) URL https://doi.org/10.1787/3197152b-en
[40] Chittum J R, Enke K A E and Finley A P 2022 The Effects of Community-Based and Civic Engagement in Higher Education: What We Know and Questions that Remain Tech. rep. American Association of Colleges and Universities Washington, DC URL https://www.aacu.org/research/the-effects-of-community-based-engagement-in-higher-education
[41] 2013 MS in Sustainability Management | Curriculum URL https://www.sustainability.ei.columbia.edu/curriculum
[42] BlackRock 2022 Learning & Development - Careers URL https://careers.blackrock.com/life-at-blackrock-2/learning-and-development/

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On the potential of Ukrainian higher educational establishments to satisfy the demand in personnel for renewable energy development

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Abstract. Green energy is a key factor for achieving global sustainable development goals. Energy safety is the basic condition for any state to function and for any economy to grow. Moreover, stable supply of energy resources is a pre-requisite for supporting adequate life quality level for the population, which is the main function of a state. In this context, the problem of training specialists in green energy has become an object of an increasing research interest in many countries, including Ukraine. Ukraine has not been experiencing any specific problems with energy security since gaining independence in 1991, except for minor issues with natural gas supply. However, in autumn and winter of 2022, the necessity to reconstruct the Ukrainian energy safety system became specifically acute. The factor having caused the problem is of a man-made nature and was brought forth by the neighboring state's military aggression. Russian military forces have been purposefully and methodically devastating the Ukrainian energy infrastructure with missile strikes over the past several months. Thanks to the technical and technological aid offered by partner countries and introducing emergency power outage schedules across the country, Ukrainian energy companies have managed to sustain the energy system in a relatively operational condition for three months by now. Nevertheless, we should envisage the future challenges and build a strategy for the post-war reconstruction of the Ukrainian energy system. Renewable energy sources have a colossal potential and may become a powerful force in the future development of Ukraine's energy industry. However, in practice, the energy industry must be supplied with a sufficient number of highly professional specialists to realize this opportunity. On the example of Ukrainian HEIs, this article offers an example and a methodology for analysing higher educational establishments' potential and preparedness to satisfy the predicted demand in personnel and to ensure sustainable development of the renewable energy market. Another finding of this research is the system of markers to measure the success of an educational programme in green energy which can be applied by educational institutions to build the programme enhancement strategy. Also, the authors define directions for perspective development of energy education in Ukraine.

1. Introduction

During the entire independence period, Ukrainian energy system has provided a stable and reliable footing for the economy. For instance, in the pre-crisis year of 2013, all areas of energy system operation collectively supplied 8.4% of the Ukrainian GDP [1]. This achievement became possible with significant natural deposits of energy minerals and fossil fuels (coal, natural gas, uranium) and the network of nuclear, thermal and hydroelectric power plants. The mentioned factors fully covered domestic consumer needs in energy resources and ensured industrial development. In addition, a share of Ukraine's energy resources was exported, which was an added source of replenishment for the state budget. Earlier studies reported that reserves of natural energy minerals in the bowels of the earth should have been sufficient for tens and even hundreds of years, which would guarantee stable energy security for Ukraine [2]. Ukraine did experience problems with supporting the economy's need in natural gas; nonetheless, the problems had been solved every time. Also, the energy sector was fully equipped with the full professional and qualification spectrum of specialists who were trained at about two hundred higher education institutions all over the country [3], although the the facilities inherent in the country's energy infrastructure still needed to be radically modernized to comply to the current national needs and global environmental requirements. At that time, the leading specialists and energy scientists were engaged in studying this issue, as well as in improving the country's energy strategy.

Russian ongoing aggression in 2014-2021 and an unprecedented large-scale military attack in 2022-2023 brought drastic and destructive changes to Ukraine's energy security. Ukrainian territories owning the greatest potential of natural energy resources and energy extraction enterprises were either occupied or annexed by the aggressor state. Since March 2022, Zaporizhzhia nuclear power plant in Enerhodar has been under occupation. While military units of the aggressor army are located on the plant's territory, they are undertaking provocative actions that undermine radiation and nuclear security [4]. Also, in the first months of the war, Kakhovka Hydropower Plant was occupied, and Okhtyrka Thermal Power Plant was demolished. As a result of airstrikes by missiles and unmanned aerial vehicles on the Ukrainian energy infrastructure, about three quarters of the country's energy production capacity had been destroyed by mid-January 2023 [4]. The experts conclude that most of the damaged objects belonging to the country's energy infrastructure cannot be reconstructed. Quite apart from the losses caused by war and hostilities, it is considered inexpedient to restore several individual objects since they were put into operation in Soviet times and by the time they were destroyed, they had reached a critical level of moral and physical wear. In the aftermath of the above-mentioned losses in the energy system, scheduled and emergency power outages for end users have been introduced throughout the country. Such measures are temporary, and their purpose is to prevent the complete failure of the Ukrainian energy system. Thanks to implementing these measures and significant technical and technological aid from the partner countries, Ukrainian energy companies manage to support the energy system of Ukraine in a relatively operational state.

The situation described above has created an impetus to realize the need for technological modernization and transformation of the Ukrainian electricity generation in the post-war period.

As can be inferred from a detailed analysis of the statements articulated by the leading specialists at the Ministry of Energy of Ukraine and the goals declared by the Energy Strategy of Ukraine until 2050, it is expected that nuclear energy will remain the basic component of energy generation in Ukraine [4]. What is more, alternative energy sources should progress, and new products and innovative technological solutions should be searched for. The above prompts us to predict that the specific share of renewable energy in the structure of the overall electricity generation will grow. The roadmap for introducing and advancing renewable energy sources will create conditions for sustainable development and satisfy the principal requirements of environmental friendliness and climate neutrality, accessibility and social justice. In addition, such an action plan fully meets the goals of integrating the Ukrainian energy system into the European ENTSO-E power grid.

Renewable energy strategies can be realized in Ukraine if two interrelated conditions are met. The first condition requires implementing technical means and innovative engineering solutions to develop renewable energy in Ukraine. These tools and solutions are costly, and it will be exceedingly difficult to implement such projects in practice independently and autonomously within a short period. Attracting grants and large-scale technical aid from developed countries together with searching for various other possibilities and sources will accelerate advancements in renewable energy.

The second mandatory condition is regular personnel supply. This condition requires from Ukraine independent and autonomous solutions. Therefore, it is urgent to assess the capacity of Ukrainian HEIs to train sufficient numbers of highly professional specialists in renewable energy on a regular basis. The success of the entire renewable energy development project in Ukraine will depend on the positive answer to this question.

Considering the above, this paper seeks to remedy these problems by analyzing the preparedness and capacity of Ukrainian HEIs to satisfy the expected demand for personnel in the growing renewable energy market.

2. Literature review

Education plays a key role in promoting environmental-friendly culture, primarily through perception and acceptance of ecological values by the youth. In recent years, this thesis has been attested by various methods and proved by scientists from such countries as the USA, China, Vietnam, Hungary, Brazil, Israel, India, Iran, Malaysia, and Nigeria [5–17]. Surveys such as those mentioned above prompted us to select the importance of educational policies in ensuring rational nature management in Ukraine as the main hypothesis of this study. In this context, growing knowledge about energy saving methods among young people and rapid transition of the economy to renewable energy sources within the framework of the practical implementation of the Sustainable Development Goals is particularly relevant.

Studies by Singh et al [8], Hoque et al [9], Friman et al [16] recommend familiarizing young people with the basics of renewable energy in primary and secondary schools through gamification, which will facilitate and promote a culture of rational energy resources use and is supposed to encourage teenagers to opt for higher education in the field of renewable energy. At the same time, Colmenares-Quintero et al [7], Kinol et al [17], and Eshiemogie et al [15] argued that significant attention should be paid to high-quality special training of energy engineering specialists by HEIs. Moreover, a study by Szeberényi et al has revealed that representatives of primary, secondary and higher schools believe that low-income families cannot afford using renewable energy sources [13]. Therefore, raising the living standard in the country is an effective factor in activating the transition to renewable energy sources. Taking into account the fact that a country's standard of living is significantly determined by the quality of higher education, sufficient attention should be paid today to improving the training quality of graduates in energy specialties at the universities. Colmenares-Quintero et al propose to improve the quality of training of energy engineers with Problem based learning and design thinking methods [7]. Ji has proved that the quality of higher education in the field of energy can be enhanced by increasing investments and strengthening the environmental component of training [11]. Saputro et al have substantiated introducing STEAM approach into the educational process that will deepen the students' comprehension of renewable energy sources [18]. Popescu et al. have indicated that introducing a pilot course on the technical, legislative and geopolitical aspects of the transition to renewable energy sources into the educational process of the university would be an advantageous approach [19]. We also fully support the conclusions made by Heffron and Foley that higher education should become the key tool for providing young people with specific knowledge and skills to prevent climate change on the planet [20]. To achieve this aim, as highlighted by Fartash et al, countries should develop a network of HEIs preparing a sufficient number of highly-qualified professionals in renewable energy and undertake in-depth research in this field [14]. It is also important for governments to foster interest and motivation among young people to obtain specific specialties in renewable energy.

3. Methods

The statistical data array analyzed in this study is drawn from five main sources.

The State Statistics Service of Ukraine has supplied data on the volume of the gross national product, the energy balance, and the number of people employed in various sectors of the economy [1]

The Unified State Electronic Database on Education in Ukraine has been used a source of information on the bachelor's and master's training programs in specialties 141 "Electrical power engineering, electrical engineering and electromechanics" and 145 "Hydropower engineering" in Ukrainian universities [3].

The normative framework has been outlined by the current legislative and regulatory acts issued by Verkhovna Rada of Ukraine and the Cabinet of Ministers of Ukraine, documents by the National Agency for Ensuring the Effective Use of Energy Resources and the International Renewable Energy Agency.

The data array obtained from the above sources served as the information base of this research. Both qualitative and quantitative methods were used in this investigation to visualize, prove and evaluate the information base:

(i) By employing the cartographic method, we attempted to visually represent the territorial distribution of Ukrainian HEIs, where training in specialty 141 "Electric power engineering, electrical engineering and electromechanics" is being delivered in the 2022-2023 academic year.

(ii) Selective and tabular methods were adopted to describe in detail the current educational programs for training bachelors and masters in the specialties 141 "Electric power engineering, electrical engineering and electromechanics" and 145 "Hydropower engineering" at Ukrainian HEIs, which focus on training professionals in renewable energy.

(iii) Logical generalization and comparative methods were used to explore and compare educational programs training specialists in renewable energy at Ukrainian HEIs with the highest contingent of students as of January 2023.

4. Results and discussion

Reducing or precluding any energy dependence of the country's economy on any other country is the basis for preserving independence, decision-making autonomy and provision for all domestic energy needs. This aspect is especially relevant if a country that owns significant reserves of energy resources pursues an overly aggressive foreign policy. The above exactly describes the situation Ukraine has recently found itself in, and one of the solutions that may be offered would be to realize the Ukraine's aspiration to autonomously provide for all the needs of the national economy in energy resources. This, among other things, can be achieved by diversifying the growing share of renewable energy in the total volume of energy generation in the country. Simultaneously, all areas of the country's life should transfer to the latest energy-efficient technologies. This will be an induced measure due to the fact that energy consumption per unit of manufactured products in the Ukrainian economy is 3-4 times higher than the similar indicators in the world's developed economies [21], whereas implementing the intended goals will allow to ensure an increase in the level of energy efficiency in Ukraine now and in the near future.

The idea of strengthening the role of renewable energy in the Ukrainian economy has been around for the past two decades and was not inspired by the war or the blackouts. In the Ukrainian legislation, the first normative documents highlighting certain aspects of developing renewable energy in the country date back to 2009. In fact, the first document discussing renewable energy in Ukraine was titled the Decree by the Cabinet of Ministers of Ukraine "On signing the Agreement on financing the program Supporting the implementation of the

Ukrainian Energy Strategy in the field of energy efficiency and renewable energy sources" No. 1524-p, dated December 16, 2009 [22]. The authority to secure the necessary financing under the 2010-2011 European Union aid program at the state level was entrusted to the National Agency for Ensuring the Effective Use of Energy Resources (now the State Agency for Energy Efficiency and Energy Saving of Ukraine [23]. In 2023, more than thirteen years after the decree was issued, the problem is still gaining momentum.

In October 2014, the Cabinet of Ministers of Ukraine approved the National Renewable Energy Action Plan for the period until 2020 [21]. Even though the deadline for implementing the plan has already passed, the document remains valid and relevant today. The document states that according to the calculations by the experts at the Institute of Renewable Energy at the National Academy of Sciences, the annual technically achievable energy potential of renewable energy sources in Ukraine is able to reach 50% of the total energy consumption in the country. In addition, the document envisaged increasing the share of renewable energy to 11.0% in the structure of Ukraine's own production. In the years preceding the war, the share of renewable energy in the structure of domestic production in Ukraine fluctuated within the range of 7.2-10.3% [24]. These data imply that it has not yet been possible to fully utilize the potential of renewable energy.

We believe that one of the reasons that did not allow the Ukrainian enterprises to unlock the utmost potential of renewable energy in Ukraine is the failure to attend to one of the most important and key components, that is, failure to provide the industry with highly qualified personnel. For instance, the National Plan had mentioned issues related to the personnel supply only twice – first, to assign the Ministry of Education of Ukraine, in collaboration with other institutions, to create educational and methodological support for the activities undertaken by centers for professional development and certification of specialists who install energy equipment that works on renewable energy sources; second – to recommend to include questions regarding the prospects for producing energy carriers from renewable energy sources and alternative types of fuel in Ukraine in the programs of educational institutions of all levels for the purpose of their popularization [21]. It follows that no questions related to training highly professional specialists in renewable energy were raised in the plan.

In December 2017, Ukraine joined the Charter and in February 2018 became a full member of the International Renewable Energy Agency (IRENA), founded in January 2009 [25, 26]. Participation in IRENA enabled Ukraine to access the world-class experience and knowledge in developing and implementing technologies for utilizing renewable energy. It is also important to receive specific practical recommendations on devising national policy provisions from the Agency's specialists. IRENA also implements measures that contribute to increasing the knowledge potential of participating countries, i.e., organizes special programs for training and education, and encourages scientific and research work. It is this function that is particularly important and relevant in the context of our research topic.

Thus, we can conclude that there is a clear understanding at the governmental level that development of renewable energy sources will become an indispensable condition for ensuring Ukraine's energy independence. In addition, renewable energy will save traditional fuel resources and improve the natural environment. However, a major step has not been taken at the regulatory level, namely, no prerequisites have been created to adequately staff the prospective renewable energy development projects.

The evidence suggests that alternative energy sources and renewable energy represent a lever for successful reconstruction of Ukraine, positive outcomes of which reach out far beyond the post-war period. However, there is a question that we cannot leave unanswered, that is, if Ukraine has sufficient human resources to achieve the ambitious goals set by the authorities. To answer this question, we will analyze the current situation in training renewable energy professionals in Ukraine. Training specialists capable of being directly engaged at renewable energy facilities in Ukraine is being delivered within two specialties: 141 Power Engineering, Electrical Engineering and Electromechanics; 145 Hydropower [3]. Specialists trained in other related specialties (142-144) can also be employed in the renewable energy sector, although after appropriate retraining.

As of January 2023, 56 institutions of higher education in Ukraine are training specialists for master and bachelor's degrees in specialty 141. The territorial distribution of educational institutions is presented in figure 1 [3].

Figure 1. Territorial distribution of educational institutions training specialists in specialty 141 "Electrical power engineering, electrical engineering and electromechanics" in the 2022-2023 academic year.

The largest number of educational institutions training students in specialty 141 are concentrated in the Ukrainian cities of Kharkiv, Kyiv and Dnipro. This distribution is natural and predictable, since these cities represent regions with a substantial number of energy infrastructure facilities and industrial enterprises that need a constant supply of personnel trained in general energy engineering. In addition, institutions of higher education in Kyiv supply specialists for the rest of Ukrainian regions, since educational degree received at one of the capital's universities is considered more prestigious.

According to our observations, training specialists in electricity is being conducted throughout Ukraine, including higher education institutions temporarily displaced due to hostilities or occupation. Examples of displaced HEIs are Volodymyr Dahl East Ukrainian National University (relocated from Luhansk to Syeverodonetsk in 2014, and later, in 2022, to Kyiv), State Higher Educational Institution "Donetsk National Technical University" (relocated from Luhansk to Pokrovsk in 2014, and to Lutsk in 2022), State Higher Educational Institution

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"Pryazovskyi State Technical University" (relocated from Mariupol to Dnipro in 2022), Donbas State Machine-Building Academy (relocated from Kramatorsk to Ternopil in 2022).

Tables 1 and 2 demonstrate that only 15 Ukrainian HEIs deliver undergraduate and/or graduate educational programs specializing in renewable energy [3]. Two educational programs are not institutionally accredited. Only four HEIs offer both bachelor and master programs.

The fact that most educational programs in renewable energy are accredited until mid-2023 or mid-2024 is of significant concern. Thus, out of 11 bachelor's level educational programs, three are accredited until July 1, 2023, and two programs are accredited until July 1, 2024. The prospects seem even gloomier for the graduate programs, since out of eight educational programs, one program is accredited until July 1, 2023, and five programs are accredited until July 1, 2024. One of the factors explaining this situation is the martial law, which has been introduced in Ukraine and which made it impossible to perform the full scope of accreditation procedures. At the same time, it cannot be guaranteed that all the existing programs will successfully renew the accreditation after the martial law expires. In other words, there is a certain risk of curtailing the currently existing educational programs.

At present, only 394 students in total are enrolled on all accredited educational programs related to renewable energy in all the four years of study. By the time the students are awarded their bachelor's diploma, it will require six months for those who are in the fourth year of study now (the nearest graduation is expected in July 2023) and up to three and a half years for those who are in the first year of study (2022 entrants are expected to graduate in July 2026). Qualified graduated bachelors will enter the labor market gradually, which will not immediately satisfy the potential demand for the number of professionals required to enable the renewable energy sector to develop intensively. In addition, some of these students will continue their studies being enrolled on graduate programs after completing the undergraduate degree, which will postpone their entry into the labor market and add another one and a half or two years to the graduation date from the undergraduate courses. At the moment, 91 students are enrolled on the existing accredited master degree educational programs in renewable energy. If these students do not choose to continue their studies at any of the postgraduate schools, they will enter the Ukrainian labor market as certified specialists in January-February 2024 and 2025.

Thus, in 2023-2026, the industry will be replenished with 485 certified professionals provided that all renewable energy education programs are successfully accredited and all students currently enrolled in education programs at the two educational levels successfully complete their studies, are awarded bachelor's and master's degrees, and join the workforce instead of joining the next educational stage.

In addition to graduates majoring in renewable energy, the Ukrainian labor market employs graduates majoring in the specialty 145 "Hydropower". Only three Ukrainian HEIs train specialists in Hydropower at undergraduate and graduate levels. These are The National University of Water and Environmental Engineering (in Rivne), Zaporizhzhia National University (in Zaporizhzhia) and National Technical University "Kharkiv Polytechnic Institute" (in Kharkiv). At all the three universities mentioned, the titles of educational programs for bachelor and master levels coincide with the name of the specialty.

Table 3 below presents the numbers of students who are pursuing an educational degree in specialty 145 "Hydropower" at Ukrainian HEIs in January 2023 [3].

The situation with accreditation seems to threaten only one educational program, which we do not consider critical. However, the number of certified specialists who will replenish the army of hydropower professionals in 2023-2026 will be only 104 specialists even under favorable conditions.

The statistical data above suggest that Ukrainian higher education institutions do not possess adequate potential to prepare more than 589 graduates in two renewable energy specialties by 2026. This number may satisfy the need in covering staff turnover and staff rejuvenation at

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Table 1. The contingent of undergraduate students majoring in Electric Power Engineering, Electrical Engineering and Electromechanics studying in educational programs in renewable energy as of January 2023.

HEI	Educational program, number of undergraduate students (persons) and state accreditation validity
O.M. Beketov National University of Urban Economy in Kharkiv	Alternative and Renewable Energy Sources 91 (accreditation valid until 01.07.2028)
Lviv Polytechnic National University	Energy Systems for Sustainable Development 77 (accreditation valid until 01.07.2023)
National Technical University of Ukraine “Igor Sikorsky Kyiv Polytechnic Institute”	Alternative and Renewable Energy Sources 75 (accreditation valid until 01.07.2023)
Odesa National University of Technology	Alternative and Renewable Energy Sources 52 (accreditation valid until 01.07.2024)
Odessa Polytechnic National University	Renewable Energy Sources and Energy Complexes 51 (accreditation valid until 01.07.2029)
National Aerospace University “Kharkiv Aviation Institute”	Alternative and Renewable Energy Sources 33 (accreditation valid until 01.07.2024)
“Zaporizhzhia Polytechnic” National University	Renewable Energy Engineering 8 (accreditation valid until 01.07.2026)
Kyiv National University of Technologies and Design	Intelligent Systems in Renewable Energy and Electric Vehicles 7 (accreditation valid until 01.07.2023)
Ukrainian State University of Railway Transport	Alternative Energy Sources and Environmentally Friendly Transportation 0 (accreditation valid until 01.07.2027)
National University “Yuri Kondratyuk Poltava Polytechnic”	Renewable Energy and Power Supply for Electric Transport 8 (no accreditation data available)
Kyiv National University of Construction and Architecture	Alternative and Renewable Energy Sources 4 (no accreditation data available)
Total number of students pursuing the accredited educational programs	394

Table 2. The contingent of graduate students majoring in Electric Power Engineering, Electrical Engineering and Electromechanics studying in educational programs in renewable energy as of January 2023.

HEI	Educational program, number of graduate students (persons) and state accreditation validity
National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute"	Alternative and Renewable Energy Sources 16 (accreditation valid until 01.07.2024)
Odesa National University of Technology	Alternative and Renewable Energy Sources 20 (accreditation valid until 01.07.2024)
Odessa Polytechnic National University	Renewable Energy Sources and Energy Complexes 15 (accreditation valid until 01.07.2025)
National Aerospace University "Kharkiv Aviation Institute"	Alternative and Renewable Energy Sources 8 (accreditation valid until 01.07.2024)
Oles Honchar Dnipro National University	Alternative and Renewable Energy Sources 15 (accreditation valid until 01.07.2023)
Kherson National Technical University	Alternative and Renewable Energy Sources 13 (accreditation valid until 01.07.2024)
National Technical University "Kharkiv Polytechnic Institute"	Sustainable and Renewable Energy: Electrical Engineering and Microelectronics 4 (accreditation valid until 01.07.2026)
Yuriy Fedkovych Chernivtsi National University	Alternative and Renewable Energy Sources 0 (accreditation valid until 01.07.2024)
Total number of students pursuing accredited educational programs	91

the existing facilities. However, ensuring the expected increase in the share of renewable energy to 25% of the total volume of electricity generation in Ukraine is unlikely to be achieved in 2035 with these numbers of graduates. In addition, we should consider that highly professional specialists in renewable energy are highly valued in the labor markets of the world's developed countries. Since the salaries in these countries considerably exceed the salaries in Ukraine, the country may face the risk of young professionals' outflow.

To diminish the migration risks and increase the applicants' interest in studying educational programs in renewable energy at Ukrainian HEIs, we recommend to introduce success markers into their content. In order to determine such markers, we have analyzed three undergraduate educational programs and three graduate educational programs in renewable energy, which had the highest contingent of students at the corresponding educational level for the time of the study. The evidence received by analyzing specified educational programs [27–32] enabled us to formulate the following markers of the program's success:

Table 3. The contingent of students majoring in Hydropower as of January 2023.

HEI	Educational program, number of undergraduate students(persons) and state accreditation validity	Educational program, number of graduate students(persons) and state accreditation validity
The National University Water and Environmental Engineering	32 (accreditation valid until 01.07.2026)	12 (accreditation valid until 01.07.2026)
Zaporizhzhia National University	29 (accreditation valid until 01.07.2028)	10 (accreditation valid until 01.07.2028)
National Technical University “Kharkiv Polytechnic Institute”	16 (accreditation valid until 01.07.2025)	5 (accreditation valid until 01.07.2025)
Total number of students pursuing the accredited educational programs	77	27

(i) highly professional teaching staff involved in delivering the educational program, their high scientific potential and practical workplace experience in the field of renewable energy, command of foreign languages at a level sufficient to teach major disciplines

(ii) providing the educational process for the educational programs with modern certified laboratories with high-tech equipment, for example, Siemens, Kinco, Hitachi-Omron, Mitsubishi Electric. This can be seen in the case of Cherkasy State Technological University, where teaching specialists in energy has been significantly enhanced with the new equipment received under USAID program. A wide range of equipment, particularly, the demonstration stands, has been deployed to deliver disciplines “Electrical and structural materials”, “Energy-saving modes and technologies”, “Industrial electronics”, which enables students, for example, to calculate solar energy, improves their professional practical skills, increases their satisfaction with the quality of the educational services and enhances the overall efficiency of the educational process

(iii) close cooperation and the availability of double degree programs with universities in France, Great Britain, the Netherlands, Spain, Portugal, Greece within the framework of EUREC graduate programs; with the universities of the Netherlands, Denmark and Norway within the framework of the Erasmus Mundus graduate programs in wind energy, with the universities of the USA, Austria and Germany within the framework of the graduate programs in renewable energy sources and sciences in the field of solar energy, etc.

(iv) introducing a practice-oriented approach to education. This can be illustrated by a positive example of collaboration between the Department of Electric Power Engineering and Control Systems (Lviv Polytechnic National University), LLC “Sambir Solar Station” and PE “Art-Energo”. The laboratory of “Renewable Electricity” was equipped with modern equipment [28]. Another example is provided by the Renewable Energy Sources department (National Technical University of Ukraine “Igor Sikorsky Kyiv Polytechnic Institute”) who initiated the Ukrainian-Polish Center for the Improvement of Renewable Energy Sources and Energy Efficiency Technologies, thanks to which both teachers and students have been acquainted with the leading experience of Polish universities and companies who are engaged in developing renewable energy and energy efficiency [29]

(v) opening possibilities for the students enrolled on the educational programs in renewable energy to participate in international mobility programs initiated by universities in the UK, Germany, Poland, Spain, etc. (with 1-2 semesters mobility period)

Replication or targeting the previously listed markers should spur demand for the educational programs in renewable energy among young people, as well as demand for the graduates among the potential employers. Implementing high-quality educational programs in renewable energy will build an effective ecosystem of electric car service in Ukraine, which will become an additional factor in improving the quality of life for the population and improve the environmental situation in the country [33]. A high-quality education will also encourage graduates to launch their own business in the field of renewable energy.

5. Conclusions

In summary, the results of this research show that in the near future, if the current situation in the specialist training in renewable energy persists, it will not facilitate achieving the goals of intensive development of renewable energy announced by the Ukrainian government. On this basis, this study formulates the most effective directions for increasing the number of highly qualified specialists in renewable energy on the Ukrainian labor market in the post-war period:

(i) increasing the level of remuneration in the renewable energy sector in Ukraine

(ii) securing more investments into the development of human capital, satisfactory working conditions and sufficient social package at renewable energy enterprises in Ukraine. Special attention should be paid to the social protection of young professionals and the development of their talents

(iii) expanding opportunities for professional development and retraining for specialists from the primary and secondary labor markets trained in specialties referred to specialism 14 to match the operational specifics related to the field of renewable energy. In this context, it is important to deploy the experience of both international renewable energy organizations and Ukrainian experience in the field of professional retraining for energy engineers

(iv) enhancing the activities performed by the HEI representatives in compliance with the requirements for successful accreditation of all current educational programs in renewable energy. In this context, it is important to focus on the best practices of the world's leading universities in specialized courses and educational programs.

(v) enriching curricula with the disciplines that acquaint students with the leading global experience in the field of renewable energy, the basics of international energy standards, and sustainable development management. It would also be beneficial to design educational programs so as to ensure the possibility of academic mobility for students, their practical training at leading renewable energy companies

(vi) launching existing educational programs at all educational levels for those HEIs where exclusively bachelors or exclusively masters in renewable energy are being trained at the moment. This will significantly expand the contingent and improve the quality of educational services

(vii) launching new educational programs in renewable energy at both undergraduate and graduate levels in Ukrainian HEIs within the scope of specialty 141. In this context, it is important to increase the level of productive cooperation between Ukrainian HEIs where specialized educational programs can launch in collaboration with the enterprises that operate in the industry

(viii) increasing the professional and qualification level of lecturers and teachers participating in delivering renewable energy educational programs. It is also important to continuously update the methodological base of the courses taught within the educational programs

(ix) increasing the prestige of the entire spectrum of professions related to renewable energy in public opinion. Regional and local authorities should play a key role in the implementation of this direction.

Implementing the above measures and the directions listed above within a short period of time will fetch a significant socio-economic and ecological effect. The social component will be ensured by reducing the number of the unemployed population and increasing the level and quality of life in Ukraine. The economic effect will manifest itself in a different way, that is, from a reduction in the Ukrainian economy's need for external energy resources to an increase in the share of energy in the gross domestic product. The country will be able to obtain an ecological effect through reducing negative consequences for the environment, which will be achievable due to a reduction in the production of the traditional energy resources.

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References

[1] 2023 State Statistics Service of Ukraine URL https://www.ukrstat.gov.ua//
[2] Top Lead 2021 Hotove doslidzhennia "Enerhetyka Ukrainy" 2021 URL https://businessviews.com.ua/energy-of-ukraine-2021/
[3] Inforesurs 2023 Reiestry | Yedyna derzhavna elektronna baza z pytan osvity [Registering educational activity subjects. The single state electronic database on education] URL https://info.edbo.gov.ua/
[4] Ministry of Energy of Ukraine 2023 URL https://www.mev.gov.ua/
[5] Khuc Q V, Tran M, Nguyen T, Thinh N A, Dang T, Tuyen D T, Pham P and Dat L Q 2023 *Urban Science* **7**(1) 13 ISSN 2413-8851 URL https://doi.org/10.3390/urbansci7010013
[6] Matana Júnior S, Antonio Leite Frandoloso M and Barbosa Brião V 2023 *International Journal of Sustainability in Higher Education* **24**(2) 462–480 URL https://doi.org/10.1108/IJSHE-07-2021-0282
[7] Colmenares-Quintero R F, Caicedo-Concha D M, Rojas N, Stansfield K E and Colmenares-Quintero J C 2023 *Cogent Engineering* **10**(1) 2164442 URL https://doi.org/10.1080/23311916.2022.2164442
[8] Singh U S, Nermend M and Singh S 2023 *Energies* **16**(1) 451 ISSN 1996-1073 URL https://doi.org/10.3390/en16010451
[9] Hoque F, Yasin R M and Sopian K 2022 *Sustainability* **14**(14) 8296 ISSN 2071-1050 URL https://doi.org/10.3390/su14148296
[10] Nasrudin D, Setiawan A, Rusdiana D and Liliasari 2022 *AIP Conference Proceedings* **2468**(1) 060019 ISSN 0094-243X URL https://doi.org/10.1063/5.0102673
[11] Ji G 2023 *Economic Research-Ekonomska Istraživanja* **36**(1) 1076–1098 URL https://doi.org/10.1080/1331677X.2022.2081236
[12] Ilham Z, Subramaniam I, Jamaludin A A, Wan-Mohtar W A A Q I, Halim-Lim S A, Ohgaki H, Ishihara K and Mansor M R A 2022 *Energy Reports* **8** 1013–1024 ISSN 2352-4847 Technologies and Materials for Renewable Energy, Environment and Sustainability URL https://doi.org/10.1016/j.egyr.2022.07.126
[13] Szeberényi A, Rokicki T and Papp-Váry Á 2022 *Energies* **15**(19) 7082 ISSN 1996-1073 URL https://doi.org/10.3390/en15197082
[14] Fartash K, Ghorbani A, Khayatian M and Elyasi M 2022 *International Journal of Energy Sector Management* **16**(3) 429–447 URL https://doi.org/10.1108/IJESM-02-2021-0023
[15] Eshiemogie S O, Ighalo J O and Banji T I 2022 *Cleaner Engineering and Technology* **6** 100388 ISSN 2666-7908 URL https://doi.org/10.1016/j.clet.2021.100388
[16] Friman H, Sitbon Y, Banner I, Einav Y and Cirella G T 2022 Sustainability and Renewable Energy Education: Children of the Next Generationt *Human Settlements. Advances in 21st Century Human Settlements* ed Cirella G T (Singapore: Springer International Publishing) pp 89–99 URL https://doi.org/10.1007/978-981-16-4031-5_6
[17] Kinol A, Miller E, Axtell H, Hirschfeld I, Leggett S, Si Y and Stephens J C 2023 *Climatic Change* **176**(2) 15 ISSN 1573-1480 URL https://doi.org/10.1007/s10584-023-03486-4
[18] Saputro H, Fitriana L, Rohman N, Bugis H and Muslim R 2022 *AIP Conference Proceedings* **2566**(1) 080002 ISSN 0094-243X URL https://doi.org/10.1063/5.0116590

[19] Popescu O, Ayala O, Flory I, Fernandez J and Jovanovic V 2022 A Pilot Course as a Step towards New Academic Programs in Renewable Energies *2022 ASEE Annual Conference & Exposition* (Minneapolis, MN) URL https://strategy.asee.org/40670
[20] Heffron R and Foley A 2022 *Nature* **607**(7917) 327 URL https://doi.org/10.1038/d41586-022-01823-8
[21] Cabinet of Ministers of Ukraine 2014 Pro Natsionalnyi plan dii z vidnovliuvanoi enerhetyky na period do 2020 roku [On the National Renewable Energy Action Plan for the Period Until 2020] URL https://zakon.rada.gov.ua/laws/show/902-2014-%D1%80#Text
[22] Cabinet of Ministers of Ukraine 2009 Pro pidpysannia Uhody pro finansuvannia prohramy "Pidtrymka vykonannia Enerhetychnoi stratehii Ukrainy v haluzi enerhoefektyvnosti ta vidnovliuvalnykh dzherel enerhii" [On the signing of the Agreement on financing the program "Supporting the implementation of the Energy Strategy of Ukraine in the field of energy efficiency and renewable energy sources"] URL https://zakon.rada.gov.ua/laws/show/1524-2009-%D1%80#Text
[23] Derzhenerhoefektyvnosti Ukrainy 2023 Welcome to Derzhenerhoefektyvnosti Ukrainy [Welcome to State the Agency on Energy Efficiency and Energy Saving of Ukraine] URL https://saee.gov.ua
[24] State Statistics Service of Ukraine 2021 Enerhetychnyi balans Ukrainy za 2020 rik [Energy balance of Ukraine for 2020] URL https://ukrstat.gov.ua/express/expr2021/11/147.pdf
[25] IRENA 2023 International Renewable Energy Agency URL https://www.irena.org
[26] 2009 Statut Mizhnarodnoho ahentstva z vidnovliuvalnykh dzherel enerhii (IRENA) [Charter of International Renewable Energy Agency (IRENA)] URL https://zakon.rada.gov.ua/laws/show/995_j02#Text
[27] OM Beketov National University of Urban Economy in Kharkiv 2022 Alternative and renewable sources of energy. Educational program
[28] Lviv Polytechnic National University 2023 Systemy enerhetyky staloho rozvytku [Energy systems of sustainable development] URL http://directory.lpnu.ua/majors/IPEC/6.141.00.09/8/2022/ua/full
[29] National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute" 2023 Osvitno-profesiina prohrama NVDE URL https://vde.kpi.ua/?page_id=342
[30] Odesa National University of Technology 2022 Alternative and renewable sources of energy. Educational program. Master's degree URL http://nmv.ontu.edu.ua/opp/141m-nvde2017.pdf
[31] National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute" 2022 Netradytsiini ta vidnovliuvani dzherela enerhii [Alternative and renewable sources of energy] URL https://osvita.kpi.ua/141_OPPM_NVDE
[32] Odessa Polytechnic National University 2022 Vidnovliuvani dzherela enerhii ta enerhokompleksy [Renewable energy sources and energy complexes] URL https://op.edu.ua/education/programs/mag-141-9
[33] Yakushev O, Hulak D, Zakharova O, Kovalenko Y, Yakusheva O and Chernyshov O 2022 *Polityka Energetyczna – Energy Policy Journal* **25**(2) 85–108 ISSN 1429-6675 URL https://doi.org/10.33223/epj/147694

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Determination of components for heat storage material

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Determination of components for heat storage material

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Abstract. Today, the world is transitioning to the 4th and 5th Generation District Heating (GDH) systems of heating networks. The main advantages of 4GDH and 5GDH are the reduction of the temperature of the coolant to +50 – +60°C and the use of various designs and operating principles of thermal energy storage. Therefore, special attention is devoted to the search for new types of coolants, heat-accumulating materials and research of their properties and determination of optimal operating modes. One of the energy storage systems that has become widespread in recent years is the mobile thermal energy storage (M-TES) that has tanks filled with heat storage material. Specially created heat storage materials are often used, which work under the necessary technological conditions and meet the strict conditions of safe transportation of liquids. This article is devoted to the search for new components for the creation of heat storage material, which will be used in capacitor-type TES together with the "thermal core", which is created from a material with a phase transition. As a result of experimental studies of the thermocycling process of water and aqueous solutions, depending on the components added, the priority components such as guar gum and xanthan gum were chosen.

1. Introduction

The rapid growth of energy consumption in industry and by the population has changed the requirements approaches to heat and power supply. To meet the ever-increasing demand, advanced economies are using more energy efficient 4GDH and 5GDH generation heating systems. Their main features are the environmental friendliness and economic expediency of the use of resources, the minimization of heat losses during heat supply, ensuring the stability of the energy and heat systems [1, 2]. The main advantages of 4GDH and 5GDH systems are:

- lowering the temperature of the coolant to +50 – +60°C, which saves energy costs for its heating;
- the use of various energy sources with a wide involvement of renewable generation sources operating with the use of thermal energy storages (TES), which makes it possible to stabilize the heat supply system and equalize peak loads [3, 4];
- the use of main pipelines to supply heat to the consumer in winter, as well as cold for the central air conditioning system in summer;
- high degree of automation and dispatching of process control.

One of the main elements in many links of energy supply are heat carriers and heat storage materials [5]. Nowadays, researchers pay great attention to the study of the thermal properties of common liquid heat carriers, heat storage materials and materials with a phase transition [6,7] and conduct active research to find new compositions as well [8, 9].

The most common coolant is water, since it has an abnormally high value of specific heat capacity of 4.2 kJ/(kg·K). This explains its ability to quickly heat up and cool down, respectively, the TES has a fast charge and discharge time. However, the main task of the TES is a long time of heat accumulation. To extend the accumulation time, multifunctional powders are used that are capable of forming water-soluble polymers (WRPs). Multifunctional powders due to their various chemical, physical and thermophysical properties are used in pharmaceutical, food, mining, paper textile, industries, as well as in construction, agriculture, oil production, etc. For research, the following substances were selected: carboxymethylcellulose, guar and xanthan gums, from which solutions were prepared with mass concentrations of 1% and 10%. The advantage is that they are able to form solutions with stable physicochemical parameters during thermal cycling. These solutions are characterized by low corrosivity, resistant to crystallization, economically viable, environmentally friendly and fire and explosion safe.

Liu et al [10, 11] propose a new approach to the heat supply system by creating M-TES, which will allow organizing a mobile heat supply process for enterprises and public utilities. Mobile heat supply is of particular importance during the war in Ukraine. The main element is a capacitive-type TES filled with accumulative substances for low-potential heating systems. For this, a test bench was created to study the process of thermocycling of heat carriers and heat storage materials.

The purpose of the research is to determine the possibility of using some components to create a heat storage material by thermocycling their aqueous solutions with subsequent use in heat storages and heat supply systems with an operating temperature range from 50℃ to 120℃.

2. Materials and methods

The choice of components for creating heat storage material was carried out taking into account the technological parameters and the specifics of its use in mobile thermal energy storage, namely:

- the rate of discharge and charge of thermal storage tanks M-TES;
- longer accumulation time;
- explosion and fire safety during transportation of M-TES;
- availability and economic feasibility of the used components.

Taking into account the specified technological requirements, some water-soluble polymers were selected for research, which we will consider in more detail [11, 12].

2.1. Materials

Carboxymethylcellulose [13,14] (CMC, food additive E466) is obtained by processing cellulose of the general composition $[C_6H_7O_2(OH)_{3-x}(OCH_2COOH)_x]_n$, where $x = 0.08 - 1.5$ (figure 1).

CMC (LLC "Khimpostachannya", China) is a substance with amorphous properties that acts as a weak acid. By its chemical nature, it is a highly polymeric ionic electrolyte.

CMC is a colorless substance that dissolves in water, has no odor and is safe to use. CMC is insoluble in vegetable oils and animal fats, does not decompose under the action of sunlight. But it dissolves in organic acids: formic, lactic and glacial acetic.

To obtain a homogeneous CMC solution, dry substances are soaked in water at a temperature of 80–85°C, then cold water is added. With an increase in temperature, the viscosity of CMC solutions decreases or phase separation or gel formation occurs.

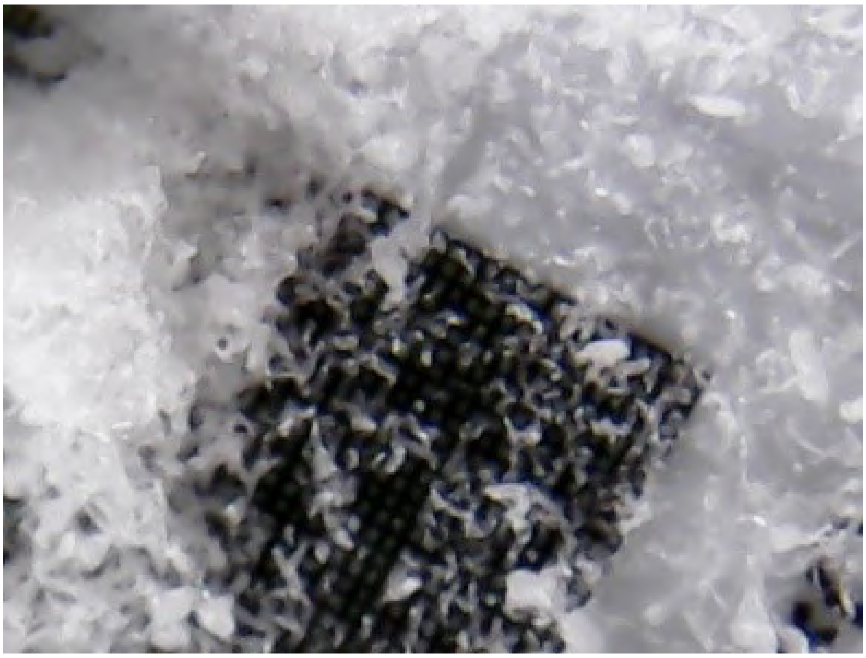

Figure 1. Carboxymethylcellulose.

Xanthan gum [15, 16] $(C_{35}H_{49}O_{29})_n$ is a natural chemical compound that is used primarily as a food additive E415 and belongs to the group of stabilizers. Xanthan gum (LLC "Khimpostachannya", China) is a linear hydrocarbon polysaccharide, the molecular weight and properties of which can be controlled by changing the living conditions of Xanthomonascampestris microorganisms (figure 2).

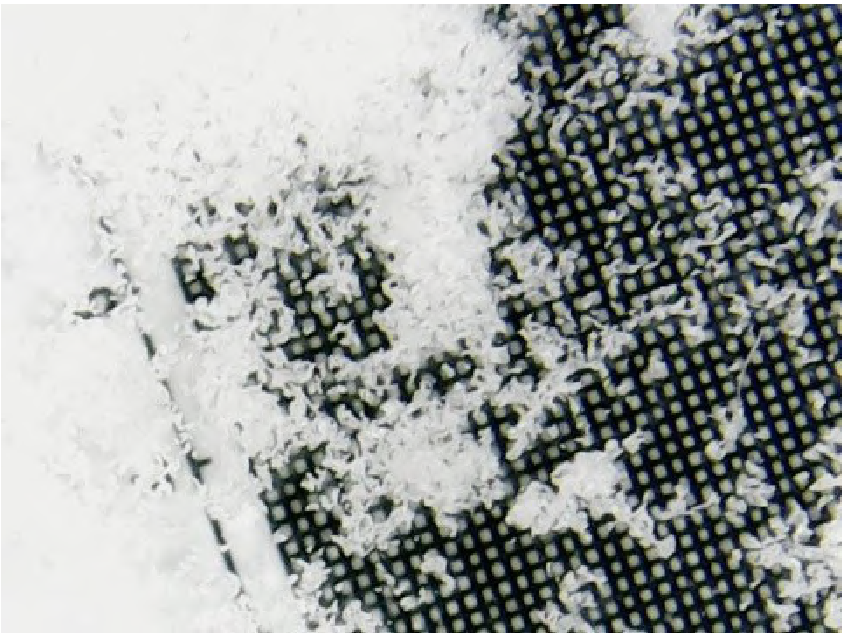

Figure 2. Xanthan gum.

Xanthan solution does not interact with alkalis and acids (except hydrochloric), alcohols and enzymes, and is also stable in the temperature range from 120 to 18°C. The water-soluble polymer (WRP) based on xanthan gum is characterized by high viscosity in the pH range from 2 to 12, therefore, a WRP with a dense structure is formed, which stabilizes foodstuffs for a long time and prolongs their shelf life.

Guar gum $(C_6H_{10}O_5)_n$ [17] is a white or yellowish powder with a characteristic odour. It is obtained from ground seeds of guar beans containing up to 70% gum (figure 3).

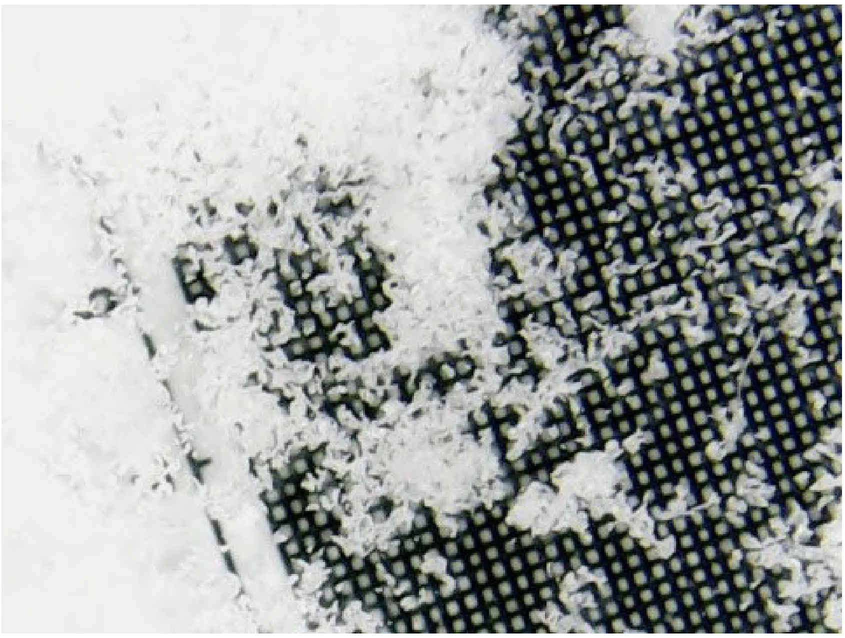

Figure 3. Guar gum.

Guar gum (TM "Zhyvy Zdorovo", Ukraine) is used as a thickening agent or stabilizer. The main advantage of natural plant polysaccharides is low cost, but their technological indicators are low, which narrows the scope of application. Therefore, chemically modified derivatives of guar, cellulose and starch are used, which have the necessary technological properties.

In the early 1970s, hydroxypropyl guar (HPG) was obtained, which became the most widely used thickener for process fluids. HPG makes it possible to obtain a polymer that is more viscous and resistant to high temperatures. Guar products typically contain 8 – 12% non-hydrated residue, HPG residue is 1 – 4%

In some experiments, a solution of sodium bicarbonate ($NaHCO_3$) with a mass concentration of 10% was used. In addition, antifreeze "DEFREEZE" (JSC "Bishofit", Ukraine) was added to the composition of the heat storage material. "DEFREEZE" is a non-toxic light yellow liquid, consisting of distilled water, natural magnesium hexahydrate, organic stabilizers and corrosion inhibitors. It does not contain synthetic and toxic substances, including ethylene, alcohols, amines, nitrites.

2.2. Test bench

The study of the thermocycling process of heat storage liquid was carried out on an experimental bench, the description of which is presented in [18]. The stand in a simplified form simulates the process that occurs in the heat storage capacity of M-TES [19]. The test bench can be represented as two containers installed one inside the other (figure 4).

A heat storage of the capacitive type has two metal containers:

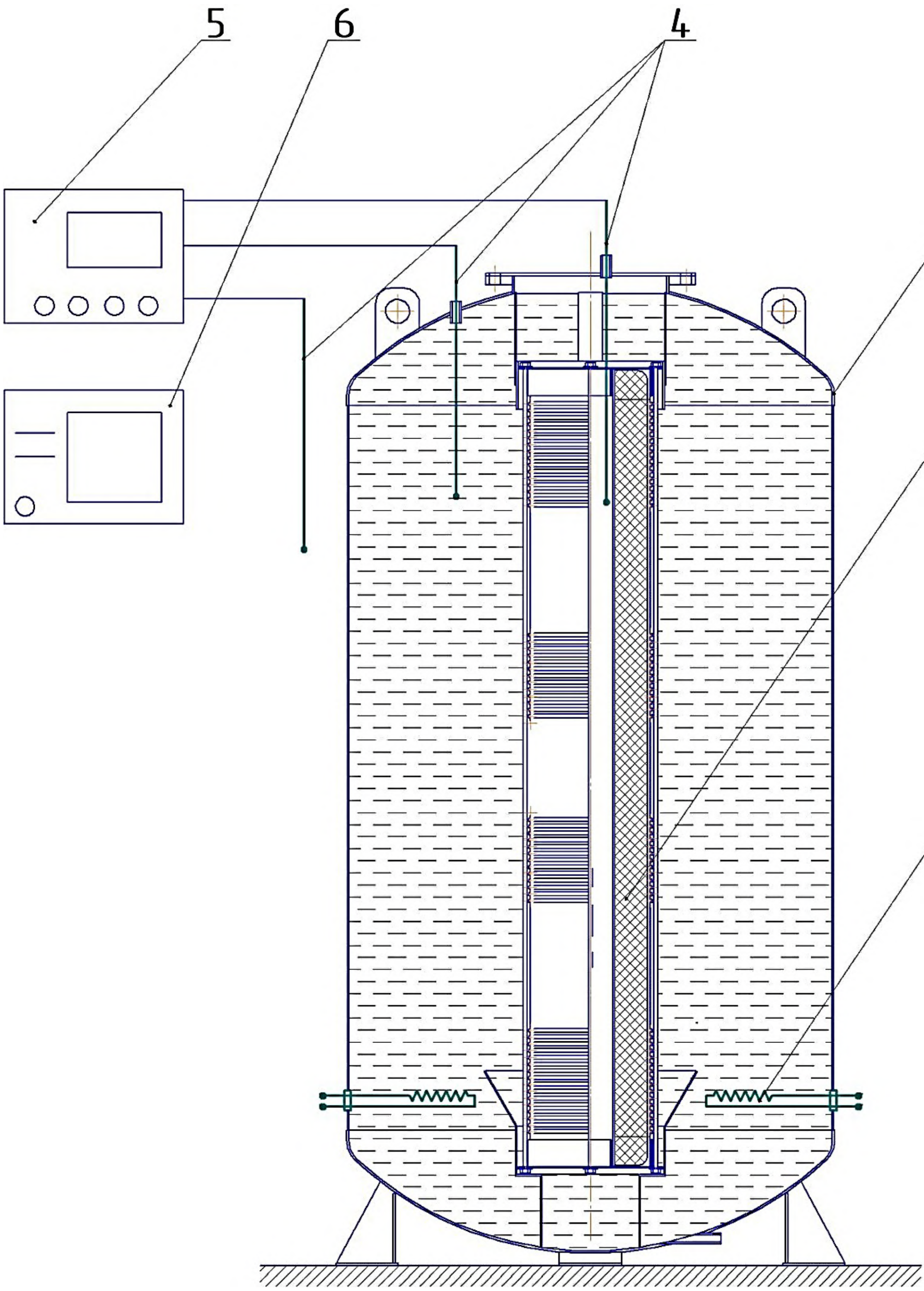

Figure 4. Test bench "Heat storage of capacitive type" (1 – tank 1, 2 – tank 2, 3 – electric heater, 4 – thermocouples, 5 – microprocessor module "TRITON 6004TS", 6 – electricity meter).

- external tank 1 filled with heat carrier (or heat storage material);
- tank 2, which is installed in the centre of tank 1, is filled with phase change material (PCM) and hermetically closed, similarly to the M-TES design. Tank 2 is called the "thermal core" and provides an increase in the heat storage capacity of the tank 1, equalizes the temperature field in the tank volume, reduces stratification by the height of the battery, shortens the "charging" time and extends the "discharging" time.

Ceresin was used to fill the "thermal core". Ceresin is PCM of natural origin, with a phase transition in the temperature range of 61 – 78°C, which coincides with the working temperatures of M-TES. Preliminary studies of specific heat capacity changes before and after thermocycling proved the feasibility of using this material [20]. Substances in tank 1 and 2 were heated by an electric heater 3 installed in the lower part of tank 1 (or an electric device in the case of an experimental stand).

The temperature was measured with thermocouples 4 using a microprocessor module "TRITON 6004TS" 5 (Scientific and Production Private Enterprise "TEREKS", Ukraine). The temperature was recorded using thermocouples and automatic cold junction temperature compensation. The main characteristics of the microprocessor module are shown in table 1.

Table 1. Technical characteristics of "TRITON 6004TS" microprocessor module.

Indicators	Value
Number of thermocouples to be connected	16 (8 diff.)
Types of used thermocouples	T, K, L, R, S and other
Input voltage range	5±19.5 mV, ±39.0 mV, ±1.17 V
Measurement cycle time	4 c
Bandwidth of input circuits	0 – 25 Hz
Cold junction compensation sensor type	PT100, PT1000
Data exchange interface	USB
Exchange speed by interface	to 115200 bit/c
The length of the communication line	to 5 m
Supply voltage	from USB, from 220 V 50 Hz
Dimensions	94 mm 160 mm 50 mm
Mass, not more than	300 g

Visualization of experimental studies was carried out using the Data Recorder software installed on a PC. Heat consumption was measured with an electric energy meter 6.

2.3. Research methodology

The studied substances in the specified combinations (table 2) are placed in tanks 1 and 2. In tank 1 samples of heat storage material with a volume of 1 liter are examined. Tank 2 contains PCM material with a volume of up to 100 ml, which was specially selected experimentally [20].

Tank 2 is the "thermal core". The volumes of the studied substances were selected in a ratio of 10:1 respectively. The containers are hermetically sealed with lids, on which are pre-installed thermocouples: t_1 is the ambient temperature; t_2 is the temperature of the water system in tank 1; t_3 is the temperature of the substance in tank 2.

Using the Data Recorder program, the visualization of the beginning of temperature measurements is observed. Meter 6 records the energy indicators. We record the indicators of the microprocessor module 5 and the heat meter 6.

Table 2. Order of heat storage materials combination when conducting experimental studies.

Number of experiment	Tank 1	Tank 2
Experiment 1	water	PCM
Experiment 2	water+antifreeze	PCM
Experiment 3	water+$NaHCO_3$	PCM
Experiment 4	water+$NaHCO_3$+antifreeze	PCM
Experiment 5	water+$NaHCO_3$+antifreeze+CMC	PCM
Experiment 6	water+guar gum (10 g)	PCM
Experiment 7	water+guar gum (1 g)	PCM
Experiment 8	water+antifreeze+guar gum (10 g)	PCM
Experiment 9	water+xanthan gum (1 g)	PCM
Experiment 10	water+antifreeze+xanthan gum (1 g)	PCM

Heating of the studied substances is carried out in the temperature range similar to the temperature load of M-TES. At the temperature of $t_2 = 85$℃, the heat supply is turned off and the temperature and power consumption continued to be measured. At the temperature $t_2 = 30$℃, the experiment is completed.

When conducting research, the following parameters are measured:

- temperature changes in the heat storage material in the tank 1, PCM in the tank 2 and the temperature of the surrounding air;
- heating and cooling time, which will allow to determine the charging and discharging time of the TES;
- energy consumption spent on heating heat storage material and material with a phase transition to the specified temperatures.

Each experiment was repeated four times. Graphical dependencies, which are based on the averaged data, are presented below.

Substances that can be added as components of the future heat-accumulating material were selected for study. The combination of substances in the tank 1 and the tank 2 are shown in table 2. The serial number of each experiment corresponds to the numbering in the figures presented in section 3 of this article.

3. Results

With the help of the "TRITON 6004TS" microprocessor module, graphical dependences of the temperature changes of the samples over time were obtained. Dependencies are built on their basis, which make it possible to evaluate the effectiveness of the components. Experiment No. 1 is chosen as a "reference" because instead of a heat storage material, water is used, the thermophysical characteristics of which are known. We will conduct a comparison relative to its results.

The energy consumption estimate for each of the experiments is shown in figure 5.

The maximum energy consumption per cycle was recorded in experiment No. 1, where water heats the PCM. The lowest energy consumption per cycle was observed in Experiment No. 10, where the heat storage material includes antifreeze and xanthan gum in the amount of 1%. The difference between these experiments is 27.3%, which is a significant difference for the average consumer and unacceptable for industry.

In experiments No. 4, No. 5 and No. 9, the energy consumption for 1 cycle is 21.5% less than in experiment No. 1 that confirms the effectiveness of using the CMC component, xanthan

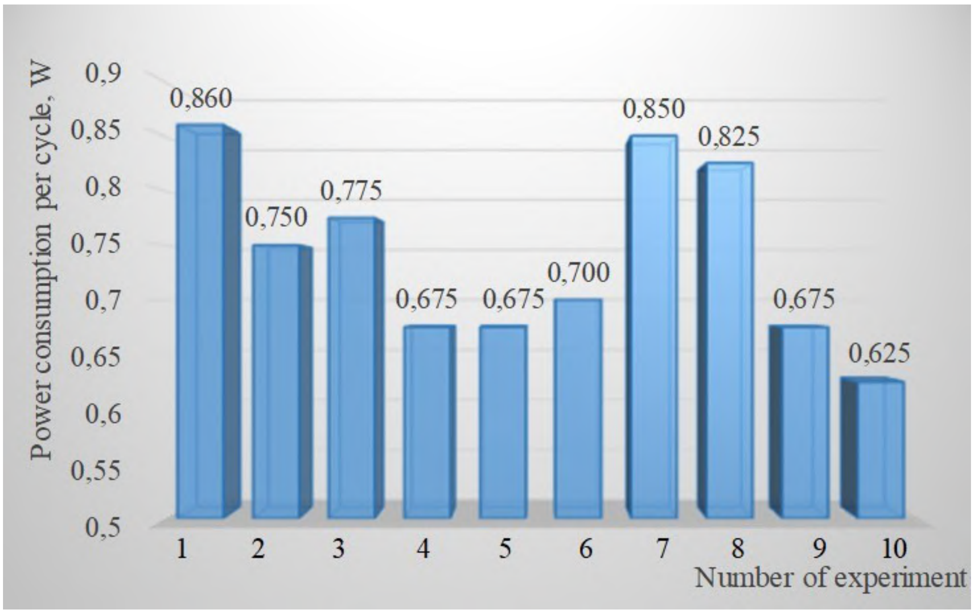

Figure 5. Average energy consumption per cycle.

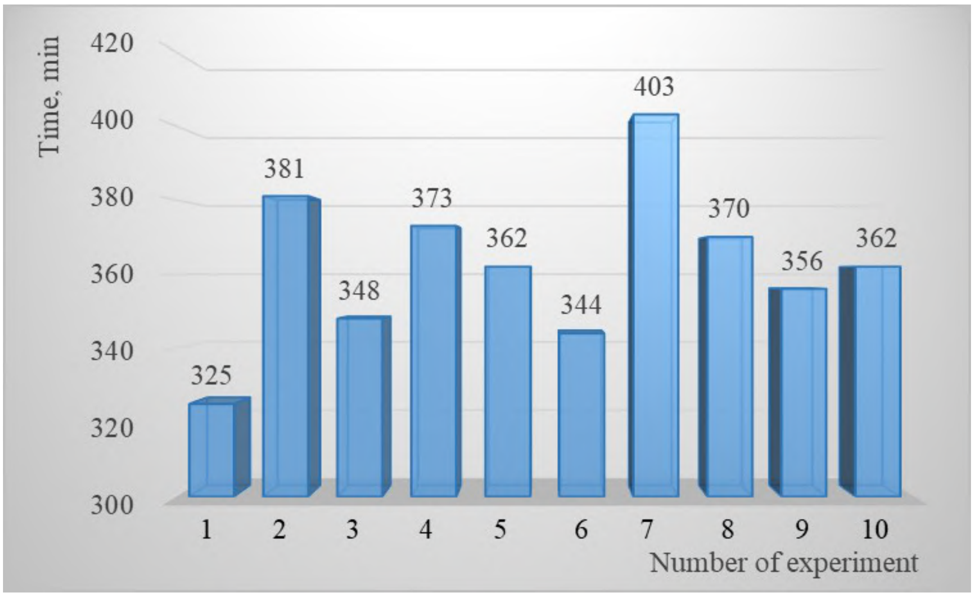

Figure 6. Average period of time per cycle.

gum, and $NaHCO_3$. In experiments No. 7 and No. 8, where guar gum is used, the results are identical to experiment No. 1.

The duration of one cycle for each experiment conducted in test bench is presented in figure 6.

The experiment time includes the heating time and the cooling time, which is equal to one cycle. It can be seen in figure 6 that the shortest cycle time was in experiment No. 1 where the water heated the PCM. This can be explained by the abnormally high specific heat capacity compared to any other liquid. In experiment No. 2, water was replaced with a heat storage material made of water and antifreeze, which extended the cycle time by 15%. But the longest cycle time is in experiment No. 7, which is 24% longer than experiment No 1, which indicates an extended period of accumulation due to the addition of 1% guar gum. Also, it is necessary to note experiments No. 4, 8, in which the cycle time is extended by 14.7% and 13.8%, respectively. But during the thermocycling process in experiment No. 4, foaming, an increase in the volume of heat storage material and a sharp smell were observed, which makes it impossible to use soda as a component. In experiments No 9 and No 10, the cycle time was increased by 9.5% and 11.4% respectively.

The ratio of the spent energy to the time of the "heating-cooling" cycle is presented in figure 7.

The ratio of the spent energy to the time of the "heating-cooling" cycle allows to assess the efficiency of the heat storage material. Therefore, experiment No. 1 is the least effective, as it

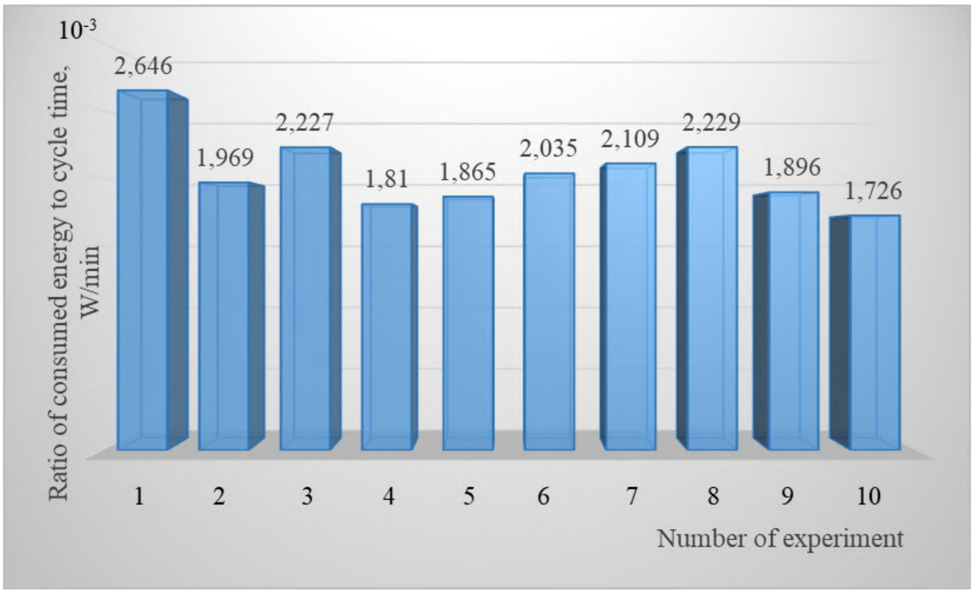

Figure 7. Ratio of energy consumption from time.

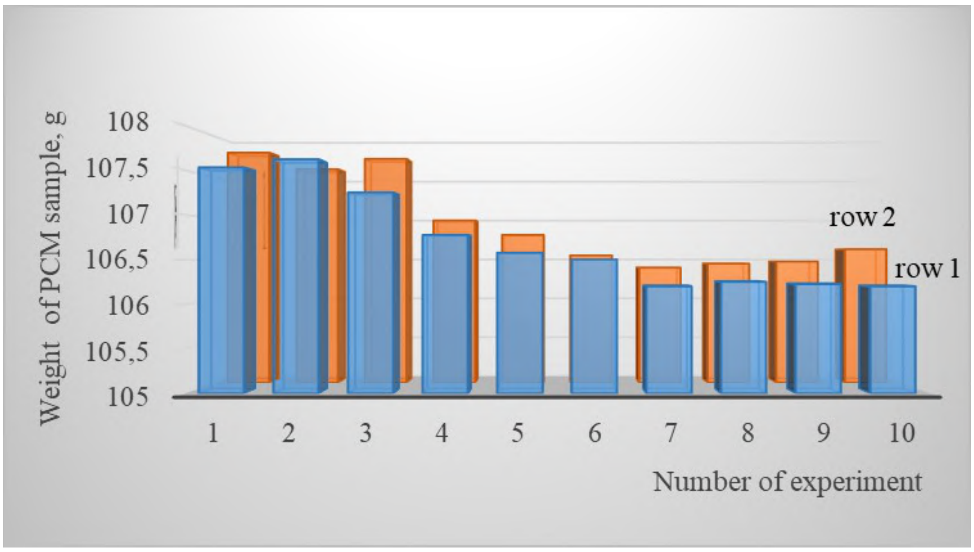

Figure 8. Dynamics of change in the weight of PCM materials (row 1 – initial mass of PCM, row 2 – final mass of PCM (after thermocycling)).

requires a significant supply of energy with a minimum accumulation time. Experiment No. 10 is the most effective, as it has the lowest value of the ratio, in general it is 34.8%. That is, when conducting further research, xanthan gum is one of the priority components.

The composition of the substance in experiment No. 2, which shows a difference from experiment No. 1 by 25.6%, is, as a rule, effective when used in heating systems of private houses. Experiments No. 4, No. 5 and No. 9 have similar results and are 31.6%, 29.5%, and 28.3%, respectively.

The dynamics of changes in the mass of PCM materials at the beginning of the research and after 40 cycles of thermocycling are shown in figure 8.

The PCM sample, in this case ceresin, was filled into container 2 and did not change throughout the entire cycle of experiments from experiment No. 1 to experiment No. 10. Weight measurements were carried out before and after thermal cycling. Samples were weighed on an Ohaus AX224 (USA) electronic balance (220g/0.1mg) with automatic calibration. The initial mass before Experiment No. 1 was 107.53 g, after the last Experiment No. 10, the mass was equal to 106.2 g. This means that in the process of 40 cycles of thermocycling (heating-cooling) the mass changed within 1 – 2% and this material can be used to fill the "thermal core" of M-TES. Such minor changes in mass, as well as the absence of volume expansion observed during the research, testify to the safety and reliability of this PCM.

4. Conclusions

The conducted experimental studies made it possible to draw the following conclusions:

- heat storage material, in addition to water and antifreeze, must contain guar gum, as they allow to create a substance that significantly extends the term of heat storage compared to water by 15 – 24%;
- the lowest energy consumption per cycle was noted with the addition of xanthan gum, this indicator decreases relative to the energy consumption of water by 27.3%. When the ratio of spent energy to the time of the thermocycling cycle is maintained, this trend is maintained and amounts to 34.8%;
- during long-term thermocycling of ceresin for up to 40 cycles, which fills the "thermal core" in the M-TES design, changes in the mass of PCM occur up to 2%, which indicates the safety and reliability of its use.

As a result of the conducted experimental studies, the expediency of using water, antifreeze, xanthan and guar gum as part of the heat storage material was established. Determining the concentrations of these substances will be the subjects of further research.

The safety of using ceresin in the "thermal core" was also confirmed by studying the change in mass before and after thermosetting.

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References

[1] Lund H, Østergaard P A, Connolly D and Mathiesen B V 2017 *Energy* **137** 556–565 ISSN 0360-5442 URL https://doi.org/10.1016/j.energy.2017.05.123
[2] Lyden A, Brown C S, Kolo I, Falcone G and Friedrich D 2022 *Renewable and Sustainable Energy Reviews* **167** 112760 ISSN 1364-0321 URL https://doi.org/10.1016/j.rser.2022.112760
[3] Xiang Y, Xie Z, Furbo S, Wang D, Gao M and Fan J 2022 *Journal of Energy Storage* **55** 105716 ISSN 2352-152X URL https://doi.org/10.1016/j.est.2022.105716

[4] Panchabikesan K, Mastani Joybari M, Haghighat F, Eicker U and Ramalingam V 2022 Analogy Between Thermal, Mechanical, and Electrical Energy Storage Systems *Encyclopedia of Energy Storage* ed Cabeza L F (Oxford: Elsevier) pp 315–328 ISBN 978-0-12-819730-1 URL https://doi.org/10.1016/B978-0-12-819723-3.00143-8

[5] Du K, Calautit J, Eames P and Wu Y 2021 *Renewable Energy* **168** 1040–1057 ISSN 0960-1481 URL https://doi.org/10.1016/j.renene.2020.12.057

[6] 2009 *Phase Change Material. Quality Assurance. RAL-GZ 896* (Sankt Augustin: RAL Deutsches Institut) URL http://www.pcm-ral.org/pdf/RAL-GZ_896.pdf

[7] Magendran S S, Khan F S A, Mubarak N M, Khalid M, Walvekar R, Abdullah E C, Nizamuddin S and Karri R R 2019 *Nano-Structures & Nano-Objects* **19** 100361 ISSN 2352-507X URL https://doi.org/10.1016/j.nanoso.2019.100361

[8] Li H, Hu C, He Y, Zhu J, Liu H and Tang D 2022 *International Journal of Heat and Mass Transfer* **192** 122869 ISSN 0017-9310 URL https://doi.org/10.1016/j.ijheatmasstransfer.2022.122869

[9] Saboori H and Jadid S 2021 *Journal of Energy Storage* **42** 103068 ISSN 2352-152X URL https://doi.org/10.1016/j.est.2021.103068

[10] Liu J, Huang Z, Fan M, Yang J, Xiao J and Wang Y 2022 *Nano Energy* **104** 107915 ISSN 2211-2855 URL https://doi.org/10.1016/j.nanoen.2022.107915

[11] Liu J, Huang Z, Fan M, Yang J, Xiao J and Wang Y 2022 *Nano Energy* **104**(Part A) 107915 ISSN 2211-2855 URL https://doi.org/10.1016/j.nanoen.2022.107915

[12] Saboori H 2023 *Sustainable Energy, Grids and Networks* **34** 101037 ISSN 2352-4677 URL https://doi.org/10.1016/j.segan.2023.101037

[13] Benslimane A, Bahlouli I M, Bekkour K and Hammiche D 2016 *Applied Clay Science* **132-133** 702–710 ISSN 0169-1317 URL https://doi.org/10.1016/j.clay.2016.08.026

[14] Kim H G, Kim Y S, Kwac L K, Shin H J, Lee S O, Lee U S and Shin H K 2019 *Nanomaterials* **9**(2) 158 ISSN 2079-4991 URL https://doi.org/10.3390/nano9020158

[15] Prabakaran R, Dhamodharan P, Sathishkumar A, Gullo P, Vikram M P, Pandiaraj S, Alodhayb A, Khouqeer G A and Kim S C 2023 *Energies* **16**(8) 3306 ISSN 1996-1073 URL https://doi.org/10.3390/en16083306

[16] Xiao Q, Zhang M, Fan J, Li L, Xu T and Yuan W 2019 *Solar Energy Materials and Solar Cells* **199** 91–98 ISSN 0927-0248 URL https://doi.org/10.1016/j.solmat.2019.04.020

[17] Yagoub N A A and Nur A O M 2013 *International Journal of Innovations in Pharmaceutical Sciences* **2**(6) 26–31 URL https://www.researchgate.net/publication/261402692

[18] Demchenko V G, Konyk A V and Falko V Y 2022 Stands and method of research on thermal cycling of phase change materials with different viscosities *Proc. XXII Int. conf. Resource-energy-saving technologies and equipment* (Kyiv: KPI) pp 54–61

[19] Demchenko V G and Konyk A V 2022 Thermal energy storage of the capacitive type UA Patent 126579

[20] Demchenko V G, Tselen B J, Konyk A V and Ivanov S O 2020 *Scientific discussion* **1**(41) 54–58 URL https://www.researchgate.net/publication/340428816

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MILP formulation of the UC-problem with boundary conditions on the autonomous forecasting horizon

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MILP formulation of the UC-problem with boundary conditions on the autonomous forecasting horizon

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Abstract. The intervals for determining the variables in the standard MILP-formulation of the UC-problem are analyzed. The need to take into account the state and load values in the pre-forecast and post-forecast time has been established. The suitability of the standard MILP-formulation of the UC-problem, problem with initial conditions, for solving dispatch control problems and the unsuitability of such a formulation for solving the generation capacity planning problems is shown. The standard MILP-formulation of the UC-problem on the cyclical forecasting interval is proposed. The suitability of the proposed MILP-formulation of the UC-problem for its application in the problem of planning the development of the generation capacity of power systems with a large share of RES is shown.

1. Introduction

The unit commitment (UC-) problem is probably the most important task in power system operation management [1–3]. The improvement of the quality of such management is provided by the use of mathematical models of the optimal load of units. The vast majority of mathematical formulations of the problem of effective management of power systems based on the criterion of minimum operating costs have the form of a problem of mixed integer linear programming (MILP) [1, 4]. The constant improvement of mathematical formulations of the UC-problem of the optimal load of units is due to the need to ensure acceptable adequacy of model solutions. In modern formulations of the UC-problem, operational characteristics of various technologies of electricity production and network restrictions on its transmission and distribution are taken into account in quite detail. In addition, each new mathematical formulation of the UC-problem is examined for its compliance with the conditions for the existence of a single optimal solution and the possibility of finding it using existing methods and available algorithms [3, 4].

Mathematical formulations of the UC problem are considered for a short-term forecast period lasting from one day to a week or a month, in some cases up to one year, with hourly reproduction of load modes of units, placement of power reserves on them, load of the transmission line network, etc. [1]

The different formulations of the UC-problem have one thing in common: they are all developed on the basis of linear time, where there are past, present, and future periods. UC-models establish a cause-and-effect relationship between the mode states of units in linear time and, as initial data, use available data on the state of units, the duration of their stay in such states, as well as on the volume of load of units and the amount of energy accumulated in electricity storage systems. Thus, known formulations of the UC-problem are problems with initial conditions.

Mathematical formulations of the UC-problem in the form of UC-constraints are used in the formulation of problems of planning the long-term development of power systems, especially power systems with a high level of penetration of renewable energy sources or extensive use of non-traditional energy storage technologies. Thus, operational costs for maneuvering, starting and stopping units, i.e. costs for ensuring the flexibility of power systems, are additionally taken into account in the formulation of the tasks of long-term development of power systems [5–10].

The planning of the development of power systems is carried out on the basis of optimization models of operating and capital costs for periods of time lasting several decades. In order to achieve the adequacy of the representation of the future load modes of power units in power system models, the costs of their start-up and power maneuvering are taken into account, which is extremely important in the conditions of penetration into the power system of a significant share of variable and unpredictable volumes of electricity production at the generating units of wind and solar power plants, as well as daily, weekly and seasonal irregularities in electricity consumption.

Usually, the simulation of load modes of power units is carried out in hourly, less often, half-hourly or fifteen-minute steps. Such detailing in time of load modes of power units is used for short periods of time lasting a day or a week and cannot be used for the entire multi-year planning period due to the excessive computational complexity of the mathematical problems that arise. Therefore, the model load modes of power units, determined on short-term forecast periods, are extended to monthly or seasonal periods, based on the assumption of periodicity of power unit load modes.

UC-models are used to simulate short-term load modes of power units. Such models were developed to solve the problems of dispatching control of the electric power system. UC-models are predictive models and require input data on the load of power units at the beginning of the forecast period, i.e., those that naturally characterize the current load mode of power units. The application of UC-models in the tasks of planning the development of power systems gives rise to two methodological problems: the first is the uncertainty of data regarding the load of power units at the beginning of each short-term planning period; the second is the non-periodicity of the model load modes of the power units.

These problems are solved below by formulating the power unit load model in the form of a UC-problem with boundary conditions.

2. Nomenclature

2.1. Indices and sets

$g \in \mathcal{G}$ Thermal generators.
$l \in \mathcal{L}_g$ Piecewise production cost intervals for generator g: $1,\ldots,L_g$.
$s \in \mathcal{S}_g$ Startup categories for generator g, from hottest (1) to coldest ($\mathcal{S}_g$).
$t \in \mathcal{T}$ Hourly time steps: $1,\ldots,T$.

The dimension of the set $\mathcal{G}$ is determined by the number of power units in the power system. The dimensions of the sets $\mathcal{L}_g$ and $\mathcal{S}_g$ are determined by the degree of detailing of the technical and economic characteristics of each power unit with regard to fuel consumption in different modes of its start-up and load. The dimension of the set $\mathcal{T}$ is determined by the duration of the simulation period and the time steps of its presentation. Usually choose a daily or weekly duration of such a period with hourly steps of its presentation.

2.2. Parameters

c_g^l	Cost coefficient for piecewise segment l for generator g (\$/MWh).
c_g^u	Cost of generator g running and operating at minimum production $\underline{P}_g$ (\$/h).
$D(t)$	Load (demand) at time t (MW).
$R(t)$	Spinning reserve at time t (MW).
$\overline{P}_g^l$	Maximum power for piecewise segment l for generator g (MW).
$\overline{P}_g$	Maximum power output for generator g (MW).
$\underline{P}_g$	Minimum power output for generator g (MW).
DT_g	Minimum down time for generator g (h).
UT_g	Minimum up time for generator g (h).
RD_g	Ramp-down rate for generator g (MW/h).
RU_g	Ramp-up rate for generator g (MW/h).
SD_g	Shutdown rate for generator g (MW/h).
SU_g	Startup rate for generator g (MW/h).
TC_g	Time down after which generator g goes cold, i.e., enters state S_g.
$\underline{T}_g^s$	Time offline after which the startup category s is available, ($\underline{T}_g^1 = DT_g$, $\underline{T}_g^{S_g} = TC_g$).
$W(t)$	Aggregate renewable generation available at time t (MW).

2.3. Variables

$p_g(t)$	Power above minimum for generator g at time t (MW), ≥ 0.
$p_W(t)$	Aggregate renewable generation used at time t (MW), ≥ 0.
$p_g^l(t)$	Power from piecewise interval l for generator g at time t (MW), ≥ 0.
$r_g(t)$	Spinning reserves provided by generator g at time t (MW), ≥ 0.
$u_g(t)$	Commitment status of generator g at time t, $\in \{0, 1\}$.
$v_g(t)$	Startup status of generator g at time t, $\in \{0, 1\}$.
$w_g(t)$	Shutdown status of generator g at time t, $\in \{0, 1\}$.
$c_g^{SU}(t)$	Startup cost for generator g at time t (\$), ≥ 0.

3. MILP formulation of the UC problem with initial conditions

We will use a MILP UC formulation based on [11]. We assume that the production cost is piecewise linear convex in $p_g(t)$, where L_g is the number of piecewise intervals and $\overline{P}_g^0 = \underline{P}_g$ is the start point of the first interval. Let generators have $UT_g > 1$. We then formulate the UC-problem as follows:

$$\min \sum_{g \in \mathcal{G}} \sum_{t \in \mathcal{T}} \left(\sum_{l \in \mathcal{L}_g} (c_g^l p_g^l(t)) + c_g^u u_g(t) + c_g^{SU}(t) \right) \tag{1a}$$

$$\sum_{g\in\mathcal{G}}(p_g(t)+\underline{P}_g u_g(t))+p_W(t)=D(t) \qquad \forall t\in\mathcal{T} \tag{1b}$$

$$\sum_{g\in\mathcal{G}} r_g(t)\geq R(t) \qquad \forall t\in\mathcal{T} \tag{1c}$$

$$p_g(t)+r_g(t)\leq(\overline{P}_g-\underline{P}_g)u_g(t) \\ -(\overline{P}_g-SU_g)v_g(t)-(\overline{P}_g-SD_g)w_g(t+1) \qquad \forall t\in\mathcal{T},\ \forall g\in\mathcal{G} \tag{1d}$$

$$p_g(t)+r_g(t)-p_g(t-1)\leq RU_g \qquad \forall t\in\mathcal{T},\ \forall g\in\mathcal{G} \tag{1e}$$

$$p_g(t-1)-p_g(t)\leq RD_g \qquad \forall t\in\mathcal{T},\ \forall g\in\mathcal{G} \tag{1f}$$

$$p_g(t)=\sum_{l\in\mathcal{L}_g} p_g^l(t) \qquad \forall t\in\mathcal{T},\ \forall g\in\mathcal{G} \tag{1g}$$

$$p_g^l(t)\leq(\overline{P}_g^l-\overline{P}_g^{l-1})u_g(t) \qquad \forall l\in\mathcal{L}_g,\ \forall t\in\mathcal{T},\ \forall g\in\mathcal{G} \tag{1h}$$

$$u_g(t)-u_g(t-1)=v_g(t)-w_g(t) \qquad \forall t\in\mathcal{T},\ \forall g\in\mathcal{G} \tag{1i}$$

$$\sum_{i=t-UT_g+1}^{t} v_g(i)\leq u_g(t) \qquad \forall t\in[UT_g,T],\ \forall g\in\mathcal{G} \tag{1j}$$

$$\sum_{i=t-DT_g+1}^{t} w_g(i)\leq 1-u_g(t) \qquad \forall t\in[DT_g,T],\ \forall g\in\mathcal{G} \tag{1k}$$

$$p_W(t)\leq W(t) \qquad \forall t\in\mathcal{T} \tag{1l}$$

$$c_g^{SU}(t)\geq c_g^s\left(u_g(t)-\sum_{i=1}^{T_g^s} u_g(t-i)\right) \qquad \forall s\in\mathcal{S},\ \forall t\in\mathcal{T},\ \forall g\in\mathcal{G} \tag{1m}$$

$$c_g^{SU}(t)\geq 0 \qquad \forall t\in\mathcal{T} \tag{1n}$$

$$p_g^l(t)\in\mathbb{R}_+ \qquad \forall l\in\mathcal{L}_g,\ \forall t\in\mathcal{T},\ \forall g\in\mathcal{G} \tag{1o}$$

$$p_g(t),r_g(t)\in\mathbb{R}_+ \qquad \forall t\in\mathcal{T},\ \forall g\in\mathcal{G} \tag{1p}$$

$$p_W(t)\in\mathbb{R}_+ \qquad \forall t\in\mathcal{T} \tag{1q}$$

$$u_g(t),v_g(t),w_g(t)\in\{0,1\} \qquad \forall t\in\mathcal{T},\ \forall g\in\mathcal{G}. \tag{1r}$$

Constraints (1b – 1r) are standard in UC problem formulations with time-varying startup costs [1, 11]. We use typical one binary formulation for startup costs using only the status variable u.

4. MILP UC formulation with initial conditions

Let's analyze the areas of definition of those restrictions, the effect of which does not coincide with the areas of definition of the unknown variables used in them.

In the functional constraints (1d), unknown values $w_g(T+1)$ of the functions $w_g(t)$ are used, which on the right go beyond the time domain of the definition of these functions. Therefore, the values of $w_g(T+1)$ should be considered as parameters, and the indicated constraints should be represented as follows

$$p_g(t)+r_g(t)\leq(\overline{P}_g-\underline{P}_g)u_g(t)- \\ (\overline{P}_g-SU_g)v_g(t)-(\overline{P}_g-SD_g)w_g(t+1) \qquad \forall t\in[1,T-1],\ \forall g\in\mathcal{G} \tag{2a}$$

$$p_g(t)+r_g(t)\leq(\overline{P}_g-\underline{P}_g)u_g(t)- \\ (\overline{P}_g-SU_g)v_g(t)-(\overline{P}_g-SD_g)w_g(T+1) \qquad t=T,\ \forall g\in\mathcal{G} \tag{2b}$$

In the next constraints (1e-1f), unknown values $p_g(0)$ of the functions $p_g(t)$ are used, which on the left go beyond the time domain of the definition of these functions. Therefore, the values of $p_g(0)$ should be considered as parameters, and the indicated constraints should be represented in the following forms

$$p_g(t) + r_g(t) - p_g(t-1) \le RU_g \qquad \forall t \in [2, T],\ \forall g \in \mathcal{G}; \tag{3a}$$
$$p_g(t) + r_g(t) - p_g(0) \le RU_g \qquad t = 1,\ \forall g \in \mathcal{G}. \tag{3b}$$

and

$$p_g(t-1) - p_g(t) \le RD_g \qquad \forall t \in [2, T],\ \forall g \in \mathcal{G}; \tag{4a}$$
$$p_g(0) - p_g(t) \le RD_g \qquad t = 1,\ \forall g \in \mathcal{G}. \tag{4b}$$

In constraints (1i), unknown values $u_g(0)$ of the functions $u_g(t)$ are used, which on the left go beyond the time domain of the definition of these functions. Considering the values of $u_g(0)$ as parameters, we will present the indicated constraints in the form

$$u_g(t) - u_g(t-1) = v_g(t) - w_g(t) \qquad \forall t \in [2, T],\ \forall g \in \mathcal{G}; \tag{5a}$$
$$u_g(t) - u_g(0) = v_g(t) - w_g(t) \qquad t = 1,\ \forall g \in \mathcal{G}. \tag{5b}$$

The area of definition of the $u_g(t)$ functions included in the constraints (1j) is shortened from the left by the value UT_g. To extend the effect of the constraints (1j) to the entire area of definition of the $u_g(t)$ functions, the unknown values $v_g(0),\ v_g(-1), \ldots, v_g(2 - UT_g)$ of the $v_g(t)$ functions should be considered as parameters, and the indicated constraints should be represented as follows

$$\sum_{i=t-UT_g+1}^{t} v_g(i) \le u_g(t) \qquad \forall t \in \mathcal{T},\ \forall g \in \mathcal{G} \tag{6}$$

Also, the area of definition of the $u_g(t)$ functions included in the constraints (1k) is shortened from the left by the value DT_g. To extend the effect of the constraints (1k) to the entire area of definition of the $u_g(t)$ functions, the unknown values $w_g(0),\ w_g(-1), \ldots, w_g(2 - DT_g)$ of the $w_g(t)$ functions should be considered as parameters, and the indicated constraints should be represented as follows

$$\sum_{i=t-DT_g+1}^{t} w_g(i) \le 1 - u_g(t) \qquad \forall t \in \mathcal{T},\ \forall g \in \mathcal{G} \tag{7}$$

Functional constraints (1m) contain values $u_g(0),\ u_g(-1), \ldots, u_g(1-TC_g)$, which should also be considered parameters.

Thus, in the presence of values of

$$w_g(T+1), \tag{8a}$$
$$p_g(0), \tag{8b}$$
$$v_g(0),\ v_g(-1), \ldots, v_g(2 - UT_g), \tag{8c}$$
$$w_g(0),\ w_g(-1), \ldots, w_g(2 - DT_g), \tag{8d}$$
$$u_g(0),\ u_g(-1), \ldots, u_g(1 - TC_g), \tag{8e}$$
$$\forall g \in \mathcal{G}$$

MILP UC formulation (1) with changes (1d) to (2), (1e-1f) to (3-4), (1i) to (5), (1j) to (6) and (1k) to (7) can be considered as a problem with initial conditions. In tasks of dispatch management, namely in tasks of short-term forecasting (a day, a week or a month ahead), the initial conditions of loading units of power system are naturally known. At the same time, the values of the $w_g(T+1)$ parameters are assumed to be zero [1].

Solving problems with initial conditions provides short-term forecasting of dynamic load modes of power system units. In general, the load regimes of the units at the beginning and at the end of the forecast period do not coincide. This means that the received forecast solutions cannot be propagated beyond the forecast interval by their periodic reproduction. Therefore, such prediction intervals are non-autonomous (figure 1).

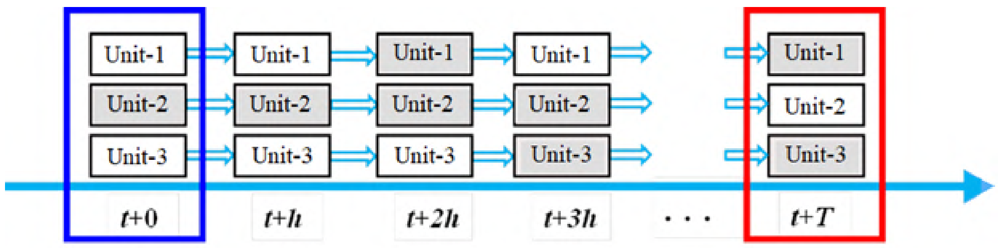


Figure 1. Non-autonomous period T of power units load in the UC-model. Loads of power units in $t{+}0$ and $t+T$ do not match.

5. MILP formulation of the UC problem with boundary conditions

Planning of long-term development of generating capacities of electric power systems is carried out on the forecasting time horizon, which is usually replaced by a representative set of short intervals of daily or weekly duration. Each short interval corresponds to a separate month or season of the selected forecast years. At such short intervals with hourly detail, the UC constraints of the optimization tasks of minimizing investment and operating costs for the entire planning horizon are formed. The UC constraints ensure the adequacy of optimization solutions in modern conditions of significant penetration of electricity production technologies from renewable energy sources and increased requirements for maneuverability and flexibility of electric power systems [2, 6–8, 10, 12].

A common drawback of the known MILP formulations of the UC problem defined on short autonomous intervals is the impossibility of providing their initial conditions. Therefore such conditions are either set arbitrarily, without justification, or are not set [2, 7, 8, 10, 12]. To avoid the need for initial conditions, the domains of the UC constraints that require such conditions are reduced. In both approaches, we have a methodological problem and its negative impact on the adequacy of solutions to the problems of planning the long-term development of electric power systems.

We propose a solution to this problem by an MILP formulation of the UC problem as an MILP formulation with boundary conditions. For this purpose let us assume that the load schedules of the power system units are periodic, that is, they repeat with a time period T (figure 2).

Taking into account the constraints (2) and equations of the type $w_g(T+1) = w_g(1)$ we

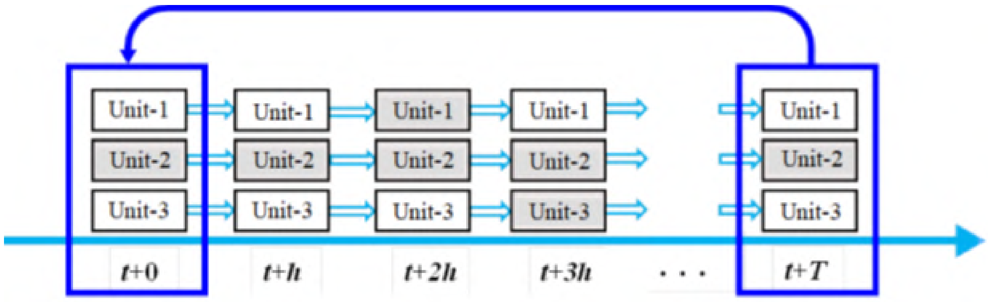


Figure 2. Autonomous period T of power units load in the UC-model. Loads of power units in t+0 and $t + T$ coincide.

obtain, respectively

$$\begin{aligned} p_g(t) + r_g(t) \le (\overline{P}_g - \underline{P}_g)u_g(t) - \\ (\overline{P}_g - SU_g)v_g(t) - (\overline{P}_g - SD_g)w_g(t+1) \qquad \forall t \in [1, T-1],\ \forall g \in \mathcal{G} \qquad (9a) \\ p_g(t) + r_g(t) \le (\overline{P}_g - \underline{P}_g)u_g(t) - \\ (\overline{P}_g - SU_g)v_g(t) - (\overline{P}_g - SD_g)w_g(1) \qquad t = T,\ \forall g \in \mathcal{G} \qquad (9b) \end{aligned}$$

Instead of constraints (3-4) with equations of the type $p_g(0) = p_g(T)$ we obtain respectively

$$p_g(t) + r_g(t) - p_g(t-1) \le RU_g \qquad \forall t \in [2, T],\ \forall g \in \mathcal{G}; \qquad (10a)$$
$$p_g(t) + r_g(t) - p_g(T) \le RU_g \qquad t = 1,\ \forall g \in \mathcal{G}. \qquad (10b)$$

and

$$p_g(t-1) - p_g(t) \le RD_g \qquad \forall t \in [2, T],\ \forall g \in \mathcal{G}; \qquad (11a)$$
$$p_g(T) - p_g(t) \le RD_g \qquad t = 1,\ \forall g \in \mathcal{G}. \qquad (11b)$$

Instead of constraints (5) with equations of the type $u_g(0) = u_g(T)$ we obtain

$$u_g(t) - u_g(t-1) = v_g(t) - w_g(t) \qquad \forall t \in [2, T],\ \forall g \in \mathcal{G}; \qquad (12a)$$
$$u_g(t) - u_g(T) = v_g(t) - w_g(t) \qquad t = 1,\ \forall g \in \mathcal{G}. \qquad (12b)$$

Instead of constraints (6) with parameters (8c) we obtain

$$\sum_{i=1}^{t} v_g(i) + \sum_{i=T-UT_g+t+1}^{T} v_g(i) \le u_g(t) \qquad \forall t \in [1, UT_g - 1],\ \forall g \in \mathcal{G}; \qquad (13a)$$
$$\sum_{i=t-UT_g+1}^{t} v_g(i) \le u_g(t) \qquad \forall t \in [UT_g, T],\ \forall g \in \mathcal{G}. \qquad (13b)$$

Similarly, instead of constraints (7) with parameters (8d) we obtain

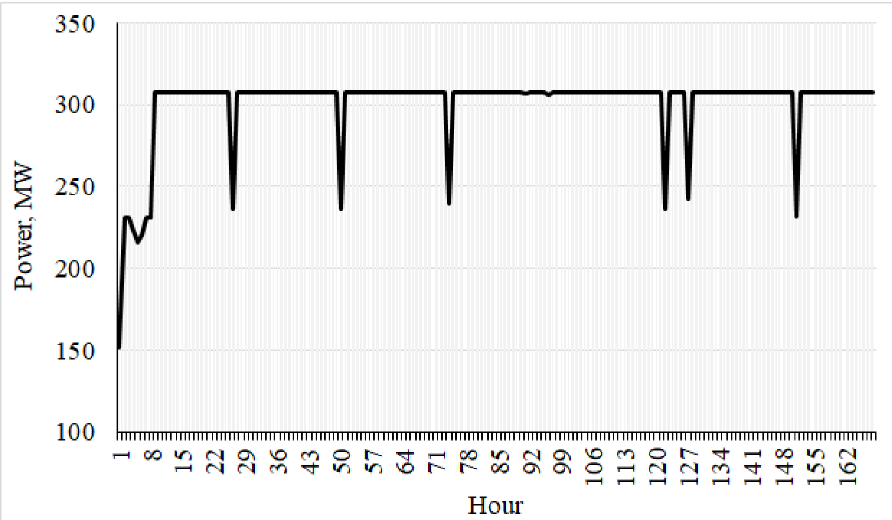
$$\sum_{i=1}^{t} w_g(i) + \sum_{i=T-DT_g+t+1}^{T} w_g(i) \le 1 - u_g(t) \qquad \forall t \in [1, DT_g - 1],\ \forall g \in \mathcal{G}; \qquad (14a)$$
$$\sum_{i=t-DT_g+1}^{t} w_g(i) \le 1 - u_g(t) \qquad \forall t \in [DT_g, T],\ \forall g \in \mathcal{G}. \qquad (14b)$$

Finally, instead of constraints (1m) with parameters (8e), we obtain

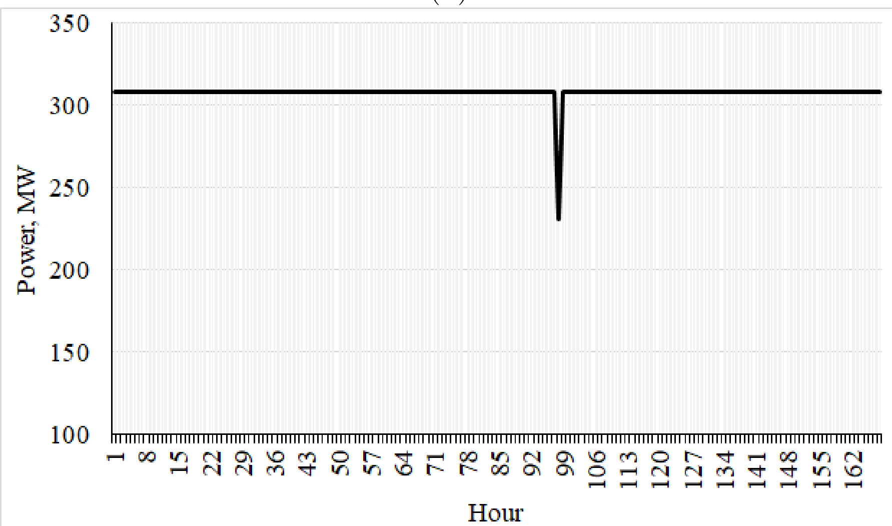
$$c_g^{SU}(t) \geq c_g^s \left(u_g(t) - \sum_{i=1}^{\underline{T}_g^s} u_g(t-i) \right) \qquad \forall s \in \mathcal{S},\ \forall t \in [\underline{T}_g^s + 1, T]\ \forall g \in \mathcal{G}; \quad (15a)$$

$$c_g^{SU}(t) \geq c_g^s \left(u_g(t) - \sum_{i=1}^{t-1} u_g(t-i) - \sum_{i=t}^{\underline{T}_g^s} u_g(T - \underline{T}_g^s + i) \right) \quad \forall s \in \mathcal{S},\ \forall t \in [1, \underline{T}_g^s],\ \forall g \in \mathcal{G}. \quad (15b)$$

MILP UC formulation (1) with changes (1d) to (9), (1e-1f) to (10-11), (1i) to (12), (1j) to (13), (1k) to (14) and (1m) to (15) can be considered as a problem with boundary conditions.



(a)



(b)

Figure 3. Weekly load schedules of NuScale power units obtained using models with (a) initial conditions and (b) boundary conditions.

The obtained MILP UC formulation is correct under the conditions

$$\underline{T}_g^s \leq T, \tag{16a}$$
$$UT_g \leq T, \tag{16b}$$
$$DT_g \leq T, \tag{16c}$$
$$\forall s \in \mathcal{S}, \forall g \in \mathcal{G}$$

Taking into account the values of the parameters $\underline{T}_g^s$, UT_g and DT_g of generating units of thermal and nuclear power plants, it is advisable to choose weekly forecasting intervals to fulfill condition (16).

6. Computational experiments with MILP formulation of the UC-problem with boundary conditions

To perform computational experiments, the MILP formulations of the UC problem with initial and boundary conditions were implemented in IBM ILOG CPLEX Optimization Studio.

The weekly graphs of the load of the generating units, obtained using the MILP formulations of the UC problem with initial and boundary conditions, are presented in figure 3. A comparison of these graphs indicates a fundamental difference between them. In the case of the MILP UC formulation with initial conditions, the graph is not autonomous and sensitive to these arbitrarily given conditions. In the case of the MILP UC formulation with boundary conditions, the graph is autonomous and can be reproduced periodically outside the weekly forecasting interval.

7. Conclusion

We proposed a new MILP formulation of the UC-problem with boundary conditions, which is intended for application on autonomous weekly time periods in the problems of planning the development of electric power systems.

The proposed UC problem with boundary conditions solves the problem of data uncertainty regarding the load of power units at the beginning of each short-term forecast period, as well as the problem of non-periodicity of power unit load modes in these periods and the impossibility of periodic distribution of such modes over much longer seasonal periods.

The proposed MILP formulation of the UC problem ensures the adequacy of planning solutions for the development of electric power systems in modern conditions of significant penetration of electricity generation technologies from renewable energy sources and increased requirements for maneuverability and flexibility of power units.

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References

[1] Knueven B, Ostrowski J and Watson J P 2020 *INFORMS Journal on Computing* **32**(4) 857–876 URL `https://doi.org/10.1287/ijoc.2019.0944`

[2] Panos E and Lehtilä A 2016 Dispatching and unit commitment features in TIMES Tech. rep. International Energy Agency, Energy Technology Systems Analysis Programme URL `https://iea-etsap.org/docs/TIMES_Dispatching_Documentation.pdf`

[3] Ringkjøb H K, Haugan P M and Solbrekke I M 2018 *Renewable and Sustainable Energy Reviews* **96** 440–459 ISSN 1364-0321 URL `https://doi.org/10.1016/j.rser.2018.08.002`

[4] Montero L, Bello A and Reneses J 2022 *Energies* **15**(4) 1296 ISSN 1996-1073 URL `https://doi.org/10.3390/en15041296`

[5] Ju Y, Wang J, Ge F, Lin Y, Dong M, Li D, Shi K and Zhang H 2019 *Applied Sciences* **9**(8) 1611 ISSN 2076-3417 URL `https://doi.org/10.3390/app9081611`

[6] Gaur A S, Das P, Jain A, Bhakar R and Mathur J 2019 *Energy Strategy Reviews* **26** 100383 ISSN 2211-467X URL https://doi.org/10.1016/j.esr.2019.100383

[7] Koltsaklis N E and Georgiadis M C 2015 *Applied Energy* **158** 310–331 ISSN 0306-2619 URL https://doi.org/10.1016/j.apenergy.2015.08.054

[8] Tejada-Arango D A, Morales-España G, Wogrin S and Centeno E 2020 *IEEE Transactions on Power Systems* **35**(3) 2012–2023 URL https://doi.org/10.1109/TPWRS.2019.2940286

[9] Diewvilai R and Audomvongseree K 2021 *Energies* **14**(18) 5733 ISSN 1996-1073 URL https://doi.org/10.3390/en14185733

[10] Schwele A, Kazempour J and Pinson P 2020 *Energy Systems* **11**(2) 247–282 ISSN 1868-3975 URL https://doi.org/10.1007/s12667-018-00321-z

[11] Knueven B, Ostrowski J and Watson J P 2020 *Mathematical Programming Computation* **12**(2) 225–248 ISSN 1867-2957 URL https://doi.org/10.1007/s12532-020-00176-5

[12] Ramírez Torrealba P J 2014 *The Role of Flexibility in Generation Expansion Planning of Power Systems with a High Degree of Renewables & Vehicle Electrification* Ph.D. thesis Imperial College London, United Kingdom URL https://spiral.imperial.ac.uk/bitstream/10044/1/44125/1/Ramirez-PJ-2015-PhD-Thesis.pdf

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Conceptual principles of forecasting demand on the day-ahead market using changes in hourly bidded demand between previous similar days

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Conceptual principles of forecasting demand on the day-ahead market using changes in hourly bidded demand between previous similar days

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Abstract. On the basis of the Law on the Electricity Market adopted in 2017, the retail electricity market in Ukraine opened on January 1, 2019, and later, on July 1, 2019, the wholesale electricity market was launched. The day-ahead market (DAM) is one of the key segments of the Ukrainian electricity market. In order to implement trading strategy and successfully conduct business, to maximize the economic results in the specified market segment, it is important to understand the market situation and the structure of demand and supply. One of the indicators that must be taken into account when planning sales in the course of one's activity is the demand for electrical energy. Currently, there are no universal algorithms in Ukraine suitable for short-term (per day) forecasting of the amount of electrical energy that will be traded on DAM. Therefore, to solve such a problem, a specialized forecasting algorithm is proposed. The basis of the developed algorithm is the possibility of considering the formulated problem in a parametric form, where, as indicators, the forecast and real data of the hourly demand on the DAM are used. At the same time, in order to find the forecast hourly demand on the market "a day ahead" – the values of the unknown indicators of the problem – an iterative method of their search is used based on statistical data of the amount of electricity purchases on the DAM, using the principle of multi-iteration analysis of changes in demand for previous similar days. The proposed algorithm is implemented in the MS Excel package, which indicates its versatility and ease of use. The high speed of obtaining a solution to the formulated problem is shown.

1. Introduction

The single-buyer model of the wholesale electricity market was also replaced by a market model based on bilateral markets, day-ahead and intraday markets, as well as balancing and ancillary services markets, where participants can freely trade electricity and power companies can provide services that ensure the stability of the power system and supply electricity to the final consumer.

One of the main segments for electricity market subjects for its purchase and sale is the DAM. Trading on DAM takes place according to the principle of margin pricing – sellers submit orders at the minimum price at which they are ready to sell, buyers – at the maximum price at which they are ready to buy. According to the results of auctions on the DAM, sellers sell at a price no cheaper than their bid, and buyers sell at a price no higher than their bid.

Hourly demand for DAM is the hourly amount of electric energy that customers declare and want to buy on DAM at the respective hourly prices. This amount directly affects both the marginal price that will be created and the amount of electricity that will be bought and sold.

According to the law of supply and demand, the lower the demand for a product, the lower the price will be; the higher the demand, the higher the price will be.

This directly affects the volumes that will be accepted for sale for sellers on the DAM. If sellers incorrectly determine the declared demand volumes and set inappropriate prices in their sales bids – either their volumes will be accepted incompletely (in case of low demand) or accepted at a low price (in case of high demand value). At the same time, in Ukraine on the DAM, volumes for purchase are usually declared at the maximum possible price, so the value of the price is actually affected by the prices in the sellers' bids, and the incorrect determination of such a price affects the economy of the seller's enterprises.

Thus, there is a need to forecast the demand for DAM. But now in Ukraine there are no mechanisms, algorithms or mathematical models that would allow forecasting with a low forecasting error.

2. Aim and tasks

The purpose of the research is to determine an algorithm that will make it possible to forecast the hourly volumes of demand for DAM for the next day, and which will have a slight deviation of the forecast indicators from the real data (that is, it will be reliable and have a forecasting error within 10%).

The tasks of the research are:

1. Determination of various algorithms for calculating forecasted hourly volumes of demand for DAM;
2. Calculation of the prediction error of each of the identified algorithms;
3. Determination of the most accurate calculation algorithm;
4. Formulaic description of the calculation algorithm.

3. Approaches to forecasting hourly demand on DAM

Trading on DAM takes place at 12:00 for the following day (we will take studying day as D). Thus, on the D-2 day, it is possible to make a forecast for D. It is clear that such forecasting is short-term, so it is fully justified to use the most current and latest data available. The scope of the current research is 4 weeks.

It is necessary to understand that the demand on DAM depends on a large number of factors [1–3]:

1. Volumes of contracted bilateral agreements;
2. Seasonality;
3. Power outage due to the destruction of critical energy infrastructure facilities;
4. Day of the week;
5. Other factors.

To obtain forecast results that are closest to the real data, it is suggested to:

1. Use the trading results for the last available day;
2. Use the change in demand between the day for which the actual results are available and the day for which the forecast is made;
3. Take into account the change in demand, for example, over the previous 4 weeks between similar days of the week.

Given the possible volatility of the DAM, as well as the fact that from day to day the conditions of the DAM vary depending on both buy and sell bids, using as a basis for calculation the data of the most recent actual trading results is reasonable and appropriate. And taking into account that depending on the day, the consumption of electrical energy by consumers changes, there is a corresponding change in the demand for DAM. At the same time, usually, such a change in demand has a predictable nature – for example, on Saturday, under normal conditions, demand decreases compared to Friday. And on Monday, on the contrary, the demand increases significantly compared to Sunday.

Thus, to calculate the forecast hourly demand for DAM on D, it is necessary to calculate a certain value of the change in this demand between the corresponding days for previous periods, then add it to the actual value of the hourly demand for DAM in D-1. But the question arises – which algorithm to use to calculate this value of the change in demand. To answer this question, it is necessary to understand, firstly, the nature of the change occurrence, and secondly, how to take into account or balance these values for previous periods.

As already mentioned, the change in demand between days of the week can occur due to the natural change in consumption for the corresponding day of the week. But this is not the only factor. We can add the following indicators:

1. Contracting on the market of bilateral contracts;
2. Change in weather conditions;
3. Change in consumption of the final consumer due to independent conditions;
4. Manipulative behavior of buyers on the DAM;
5. Other factors (for example, an error when entering data on the trading platform).

It is clear that some of these indicators cannot be predicted and they can distort the final result of the calculation, worsening the accuracy of forecasting. But a certain mechanism or algorithm should be provided, which would allow either to reduce the influence of these indicators, or to reject these values.

Another aspect is the question of taking into account the value of the change in hourly demand for the calculation of the forecasting value. Actually, the answer to this question will give an understanding of how the calculation will be carried out. For comparison, 4 calculation options are considered:

1. As the arithmetic mean value of the change in demand;
2. As a weighted average value of the sum of positive and negative changes in demand, weighted by the number of days with a positive change in demand and a negative change in demand, giving preference to those days that are more in number (by increasing their weight) and that are closer to today's day. The essence of the algorithm is as following:
   (a) the number of days with positive and negative changes in demand is determined;
   (b) if all days have either a positive change or a negative one, then the arithmetic mean is calculated – there is no need for weighting;
   (c) if there are more days of a certain type, the weight of that type increases (one plus the ratio of the number of such days to the total number of days), and the weight of another type decreases (one minus the ratio of the number of such days to the total number of days);
   (d) if the number of days of both types is equal, then the arithmetic mean of the former two days, multiplied by 0.5, plus the arithmetic mean of the latter two days, multiplied by 1.5, is calculated).
3. As a weighted average value of the sum of positive and negative changes in demand, weighted by the number of days with a positive change in demand and a negative change in demand,

giving preference to those type of days that are more in number (by increasing their weight). The essence of the algorithm is as following:

(a) the number of days with positive and negative changes in demand is determined;
(b) if all days have either a positive change or a negative one, then the arithmetic mean is calculated – there is no need for weighting;
(c) if there are more days of a certain type, the weight of that type increases (one plus the ratio of the number of such days to the total number of days), and the weight of another type decreases (one minus the ratio of the number of such days to the total number of days).

4. As a weighted average value for positive and negative changes in demand, taking into account the deviation from the arithmetic mean of the absolute values of changes in demand to determine atypical days (determined by the author by experimental method to remove such atypical days). The calculation algorithm is as following:
   (a) the sum and number of positive and negative days are calculated, the arithmetic mean of absolute values among changes in demand is determined;
   (b) an iterative process of discarding non-typical days to reduce the influence of non-representative values on the final value of the forecast. For this, the so-called "deviation weight" is calculated by calculating the inverse of the relative deviation for each value of the change in demand from the calculated arithmetic mean. If the calculated value is less than 0, such an indicator of the change in demand is rejected and a recalculation is made, starting from the first stage, but already without this indicator. After the iterative process, the average value of the "deviation weight" is calculated separately for positive changes in demand, separately for negative changes in demand;
   (c) adjustment of the weight of positive values of changes in demand (or negative values – the value of the adjustment will be reversed for positive values – there is no significant difference). Weight values for positive changes in demand are adjusted by this factor. After that, the weighted average forecast value of the change in demand for the day under study is calculated, where the weight is the adjusted values of the "deviation weights".

It is worth to mention that in practice the most accurate forecasting results come from similar hours from previous day. Such principle is behind reasoning of using previous day (D-1) as a basis for adding certain value of change in demand between the corresponding days for previous periods.

For calculations in the algorithms and comparison of forecast calculated values with real data, real data of hourly demand based on the results of auctions on DAM in the period from July 30, 2022 to August 31, 2022 are used. In order to simplify the calculations, verify the reliability of the proposed algorithms and achieve the set goals, the depth of the analysis of the change in demand is 4 previous weeks, therefore, the actual hourly demand data based on the results of the DAM trades from July 1, 2022 were used for the analysis in the calculations.

4. Algorithms calculation results

Calculations for the proposed algorithms were performed in the MS Excel software package. This ensures the universality and ease of use of the specified calculations, is clear and shows a high speed of solving the tasks and low or even zero costs for the implementation of the algorithm.

The results of the calculations are presented in the form of a comparative table. Figure 1 shows an example of the results of the forecast calculation and real data based on the results of the DAM auctions.

Figure 2 shows an example of the absolute deviations of each of the algorithms from the real data based on the results of the DAM auctions: real data minus forecast data. At the same

Day	Hour	Forecast 1	Forecast 2	Forecast 3	Forecast 4	Real data
30.07.2022	1	1 496,300	1 626,500	1 626,500	1 501,200	1 243,000
30.07.2022	2	1 214,600	1 214,600	1 214,600	1 207,100	1 163,300
30.07.2022	3	1 108,200	1 108,200	1 108,200	1 090,300	1 010,100
30.07.2022	4	978,600	1 053,800	1 053,800	923,600	884,600
30.07.2022	5	929,200	929,200	929,200	943,800	841,000
30.07.2022	6	1 060,300	1 118,200	1 118,200	1 077,800	923,700
30.07.2022	7	1 039,800	1 039,800	1 039,800	1 039,400	1 129,900
30.07.2022	8	831,300	751,100	751,100	696,100	1 225,500
30.07.2022	9	866,600	748,700	748,700	786,000	1 493,700
30.07.2022	10	750,300	533,500	533,500	666,500	1 543,900
30.07.2022	11	569,100	327,200	327,200	456,400	1 556,000
30.07.2022	12	530,000	278,200	278,200	461,300	1 510,000
30.07.2022	13	624,500	638,700	624,500	647,500	1 448,400
30.07.2022	14	657,100	672,700	657,100	661,500	1 429,600
30.07.2022	15	520,500	274,000	274,000	413,300	1 509,100
30.07.2022	16	488,900	243,300	243,300	403,400	1 526,100
30.07.2022	17	601,300	394,500	394,500	500,400	1 633,200
30.07.2022	18	774,800	642,100	642,100	667,400	1 506,900
30.07.2022	19	1 044,000	1 044,000	1 044,000	1 015,800	1 316,400

Figure 1. Calculation results of every algorithm and real data.

time, the most accurate algorithm is highlighted in green, and the least accurate in red.

It should be noted that this calculation will be used both to determine the relative error of forecasting (figure 3), and further to determine which of the algorithms turned out to be the most accurate both in terms of the smallest deviation for the entire period and in terms of the number of hours, in which it was more accurate.

Table 1 presents a comparison of the calculation results of all four algorithms. Presented data on the sum of absolute values of absolute deviation and the number of times such algorithms were more accurate than others. There should be noted two things:

1. If more than one type of algorithm was the most accurate in one hour (the same result of the forecast calculation) – all such algorithms are considered as more accurate for the corresponding hour. The larger the value, the greater the number of times the algorithm was more accurate;
2. Regarding the sum of absolute values of absolute deviations – this value is exclusively informative for comparing all algorithms and determining the one that was closer to the real data based on the results of the auctions on the DAM. The smaller the value, the more accurate the algorithm.

As can be seen from the table 1, Algorithm 4 shows both the smallest deviation from the real data and the largest number of times when it was more accurate. At the same time, the application of algorithm 4 allows both the rejection of atypical days (which is impossible when applying algorithm 1) and the monitoring of atypical behavior of market participants when submitting bids on the DAM.

Table 2 illustrates the calculation results and accuracy of algorithm 4 for a typical day.

Day	Hour	Absolute deviation 1	Absolute deviation 2	Absolute deviation 3	Absolute deviation 4
30.07.2022	1	-253,300	-383,500	-383,500	-258,200
30.07.2022	2	-51,300	-51,300	-51,300	-43,800
30.07.2022	3	-98,100	-98,100	-98,100	-80,200
30.07.2022	4	-94,000	-169,200	-169,200	-39,000
30.07.2022	5	-88,200	-88,200	-88,200	-102,800
30.07.2022	6	-136,600	-194,500	-194,500	-154,100
30.07.2022	7	90,100	90,100	90,100	90,500
30.07.2022	8	394,200	474,400	474,400	529,400
30.07.2022	9	627,100	745,000	745,000	707,700
30.07.2022	10	793,600	1 010,400	1 010,400	877,400
30.07.2022	11	986,900	1 228,800	1 228,800	1 099,600
30.07.2022	12	980,000	1 231,800	1 231,800	1 048,700
30.07.2022	13	823,900	809,700	823,900	800,900
30.07.2022	14	772,500	756,900	772,500	768,100
30.07.2022	15	988,600	1 235,100	1 235,100	1 095,800
30.07.2022	16	1 037,200	1 282,800	1 282,800	1 122,700
30.07.2022	17	1 031,900	1 238,700	1 238,700	1 132,800
30.07.2022	18	732,100	864,800	864,800	839,500
30.07.2022	19	272,400	272,400	272,400	300,600

Figure 2. Calculation results of every algorithm and real data.

Table 1. Algorithms calculation results comparison of aggregated deviation data and number of more accurate calculations.

Parameter	Algorithm			
	1	2	3	4
Sum of modules of absolute deviations	224 284.7	249 400.7	249 763.7	219 057.9
Times of being more accurate	322	201	196	360

5. Description of the most accurate algorithm

Calculations can be made in D-2 after receiving the actual results of the auctions on the DAM in D-1. It should be noted that all calculations are performed separately for each hour h.

1. Calculating demand change on the DAM for the previous 4 weeks w for the following days d: D-6 and D-7, D-13 and D-14, D-20 and D-21, D-27 and D-28:

$$\triangle A_w^h = A_{d+1}^h - A_d^h \tag{1}$$

2. Calculating sum of positive and negative A_w^h separately:

$$A_{w,pos}^h = \sum \triangle A_w^h \texttt{ for } \triangle A_w^h > 0 \tag{2}$$

$$A_{w,neg}^h = \sum \triangle A_w^h \texttt{ for } \triangle A_w^h < 0 \tag{3}$$

3. Calculating separate number of positive N_{pos}^h for $\triangle A_w^h > 0$ and negative N_{neg}^h for $\triangle A_w^h < 0$.

Day	Hour	Relative deviation 1	Relative deviation 2	Relative deviation 3	Relative deviation 4
30.07.2022	1	-20%	-31%	-31%	-21%
30.07.2022	2	-4%	-4%	-4%	-4%
30.07.2022	3	-10%	-10%	-10%	-8%
30.07.2022	4	-11%	-19%	-19%	-4%
30.07.2022	5	-10%	-10%	-10%	-12%
30.07.2022	6	-15%	-21%	-21%	-17%
30.07.2022	7	8%	8%	8%	8%
30.07.2022	8	32%	39%	39%	43%
30.07.2022	9	42%	50%	50%	47%
30.07.2022	10	51%	65%	65%	57%
30.07.2022	11	63%	79%	79%	71%
30.07.2022	12	65%	82%	82%	69%
30.07.2022	13	57%	56%	57%	55%
30.07.2022	14	54%	53%	54%	54%
30.07.2022	15	66%	82%	82%	73%
30.07.2022	16	68%	84%	84%	74%
30.07.2022	17	63%	76%	76%	69%
30.07.2022	18	49%	57%	57%	56%
30.07.2022	19	21%	21%	21%	23%

Figure 3. Calculation results of every algorithm and real data.

4. Calculating arithmetic mean of absolute values $\triangle A_w^h$:

$$A_{aver,abs}^h = \frac{\sum |\triangle A_w^h|}{N_{pos}^h + N_{neg}^h} \tag{4}$$

5. Calculating first iteration of absolute value of inverse relative deviation $|\triangle A_w^h|$ from $A_{aver,abs}^h$ for all $\triangle A_w^h$ (so-called "weight of deviation"):

$$D_{w,weight,I}^h = 1 - \left| \frac{|\triangle A_w^h| - A_{aver,abs}^h}{(A_{aver,abs}^h} \right| \tag{5}$$

If value $D_{w,weight,I}^h < 0$ then $\triangle A_w^h$ significantly deviates compared to other indicators, so it must be discarded, zeroed and recalculation should be done (II iteration) and calculate $N_{pos,iter-last}^h$, $N_{neg,iter-last}^h$ and $D_{w,weight,iter-last}^h$. Such recalculations (iterations) are performed until there are no significant deviation. Maximum number of iterations in this example will be four (equalizes to the number of analyzed $\triangle A_w^h$).

6. After the final iteration average value of the sum $D_{w,weight,iter-last}^h$ is calculated separately for positive and negative A_w^h, if the number of such values is not 0:

$$D_{w,weight,iter-last,pos}^h = \frac{\sum D_{w,weight,iter-last}^h}{N_{pos,iter-last}^h} \text{ for } \triangle A_w^h > 0, N_{pos,iter-last}^h <> 0 \tag{6}$$

$$D_{w,weight,iter-last,neg}^h = \frac{\sum D_{w,weight,iter-last}^h}{N_{neg,iter-last}^h} \text{ for } \triangle A_w^h < 0, N_{neg,iter-last}^h <> 0 \tag{7}$$

Table 2. Accuracy of algorithm 4 on the example of one day (04.08.2022).

Hour	Demand forecast	Real data demand	Absolute deviation	Relative deviation
1	1 328.6	1 305.1	-23.5	-2%
2	1 039.4	1 090.7	51.3	5%
3	956.1	992.8	36.7	4%
4	920.4	907.1	-13.3	-1%
5	890.6	933.9	43.3	5%
6	1 031.4	1 058.0	26.6	3%
7	1 277.8	1 245.4	-32.4	-3%
8	1 454.2	1 452.9	-1.3	0%
9	1 810.3	1 719.0	-91.3	-5%
10	1 840.6	1 835.4	-5.2	0%
11	1 961.5	1 926.2	-35.3	-2%
12	1 939.0	1 887.2	-51.8	-3%
13	1 860.3	1 864.7	4.4	0%
14	1 735.1	1 755.5	20.4	1%
15	2 037.0	1 954.4	-82.6	-4%
16	2 082.8	1 923.4	-159.4	-8%
17	1 867.0	1 855.4	-11.6	-1%
18	1 685.6	1 649.8	-35.8	-2%
19	1 669.9	1 625.0	-44.9	-3%
20	1 723.2	1 807.2	84.0	5%
21	1 697.2	1 856.9	159.7	9%
22	1 721.9	1 930.2	208.3	11%
23	1 505.5	1 575.0	69.5	4%
24	1 592.3	1 542.2	-50.1	-3%
Total	37 627.7	37 693.4	65.7	0%

7. Calculating the value of corrected weight for positive $\triangle A_w^h$:
   (a) if $N_{pos,iter-last}^h = 0$ or $N_{neg,iter-last}^h = 0$ or $N_{pos,iter-last}^h = N_{neg,iter-last}^h$ then
$$W_{corrected}^h = 1 \tag{8}$$
   (b) otherwise
$$W_{corrected}^h = \frac{N_{pos,iter-last}^h}{N_{neg,iter-last}^h} \cdot \frac{D_{w,weight,iter-last,neg}^h}{D_{w,weight,iter-last,pos}^h} \tag{9}$$
8. Calculating corrected value of $D_{w,weight,corrected}^h$ for positive $\triangle A_w^h$:
$$D_{w,weight,corrected}^h = D_{w,weight,iter-last}^h * W_{corrected}^h \text{ for } \triangle A_w^h > 0 \tag{10}$$
$$D_{w,weight,corrected}^h = D_{w,weight,iter-last}^h \text{ for } \triangle A_w^h < 0 \tag{11}$$
9. Calculating average weighted value of demand change $\triangle A_{weighted}^h$ on the DAM:
$$\triangle A_{weighted}^h = \frac{\sum \left(\triangle A_w^h * D_{w,weight,corrected}^h \right)}{\sum D_{w,weight,corrected}^h} \tag{12}$$

10. Calculating forecasted value of the demand on the DAM:

$$A_D^h = A_{D-1}^h + \triangle A_{weighted}^h \tag{13}$$

This concludes formulaic expression of researched algorithm. Provided that there is one of the main goals of EU as being climate neutral by 2050, companies need to achieve such goal and remain economically profitable at the same time. Therefore it is necessary to conduct business with the aim of maximizing its finances at the every possible situation and market – such as DAM [4].

6. Conclusions

To this day, achieving environmental goal as being climate neutral for most EU countries is still a challenge, taking into account the need to get rid of one of the most largest sources of emissions – coal – by 2030. Although the increase in energy resource prices and their shortage in Europe during the last months of 2022 has created new challenges for achieving environmental goals in the EU and Ukraine.

Forecasting the demand on the DAM is one of the components that must be carried out for successful business and optimization of business processes of trading companies in the electricity market. Given that quite often the income of such companies depends on how they will sell on the DAM, the choice of the correct approach to forecasting is quite acute.

In the article, four algorithms for forecasting the hourly demand for DAM are considered, corresponding calculations are performed, and a comparative analysis of the calculation results is carried out. For each of the algorithms, their prediction errors were calculated and the most accurate algorithm out of four was determined.

A formulaic description of the most accurate algorithm is given – as a weighted average value for positive and negative changes in demand, taking into account the deviation from the arithmetic mean of the absolute values of changes in demand to determine atypical days. Forecasting is carried out on the basis of statistical data on the amount of electricity purchases on the DAM, using the principle of multi-iteration analysis of changes in demand for previous similar days of previous months (with the possibility of increasing the sampling depth to quarters or years). At the same time, it should be noted that all calculations were performed in the MS Excel package, which indicates their ease, availability, speed, as well as the low or zero cost of implementing such an algorithm.

As a result of the application of the specified algorithm, there is also the possibility of tracking atypical behavior of market participants on the DAM, which will require additional attention and research.

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References

[1] Singh A K, Ibraheem S K, Muazzam M and Chaturvedi D K 2013 *Network and Complex Systems* **3**(3) 38–48 URL `https://www.iiste.org/Journals/index.php/NCS/article/view/6072`
[2] Solyali D 2020 *Sustainability* **12**(9) 3612 ISSN 2071-1050 URL `https://doi.org/10.3390/su12093612`
[3] Krutsyak M 2018 *Ekonomichnyy analiz* **28**(3) 37–46 ISSN 2219-4649 URL `https://doi.org/10.35774/econa2018.03.037`
[4] Stanytsina V, Artemchuk V, Bogoslavska O, Zaporozhets A, Kalinichenko A, Stebila J, Havrysh V and Suszanowicz D 2022 *Energies* **15**(19) 7215 ISSN 1996-1073 URL `https://doi.org/10.3390/en15197215`

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Line electrical transmission damage identification tool in distributors electrical networks

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Line electrical transmission damage identification tool in distributors electrical networks

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Abstract. In the paper showing that one of the main way for Ukraine electric power industry evolution is electric power networks and systems improvement and construction considering Smart Grid concept. The main idea of Smart grid is the reliable, energy-efficient and high-quality energy supply system. To implement the idea, it is necessary to create a high-performance information and computing infrastructure. The main components of Smart Grid is emergency mode diagnostics and damage monitoring. Providing fault diagnostics and fault monitoring can improve the power supply reliability and quality to consumers. So, the task of quickly and accurately determining the place of damage is important. In the article showing that emergency detection tools in sections of both cable and overhead electrical networks it's a way to improve efficiency of the networks. The diagram of the placement of damage indicators on the section of the electrical distribution network is presented, which allows determining the direction of the search for the location of the damage. A comparative analysis of measuring current transformers of optical and electromagnetic type was carried out. It is shown that a significant number of advantages of optical measuring current transformers, which can be used in damage indicators, can be provided by measuring current transformers of the electromagnetic type. Creating fault indicator based on the Smart Grid concept lets do to reduce searching time for the cause and location of an emergency situation to a minimum. In this concept application fault indicator in energy grid ensure it connection to operating overhead and cable lines without removing voltage by connecting the output of the secondary winding of the measuring current transformer of the detachable design to the measuring converters directly placed near the current measuring transformers with the help of a mechanical spring fastener. A block diagram of a specialized information-measuring system with a damage indicator was created, taking into account the requirements of the Smart Grid concept, which allows to reduce the time of searching for the cause to a minimum.

1. Introduction

Ensuring the effective and safe functioning of the electric power complex of Ukraine largely depends on the stability of the work of its individual components, which are united by a common mode of production, transmission and distribution of electric and thermal energy with common centralized control [1]. The existing course ”smart grids” position concept's implementation in Ukraine until 2035 is aimed at the active development of Smart Grid systems in the energy system of Ukraine and is fully in line with the priority directions of energy development in the EU.

Thus, one of the important directions of the development of the electric power industry both in the world and in Ukraine is the improvement and construction of electric power networks and systems according to the Smart Grid concept [2,3]. The main idea of Smart grid is the reliable, energy-efficient and high-quality energy supply system. To implement the idea, it is necessary to create a high-performance information and computing infrastructure.

Violation of the operation mode of any of the components of the energy system leads to the emergence of various emergency situations. The most common types of damage are accidents caused by short-circuits and short-circuits to the ground. It is believed that accidents caused by short-circuits make up 70–80% [4]. One of the most common places of damage in electrical networks is cable and overhead power lines (power lines).

Therefore, monitoring the parameters of the emergency modes of cable lines and power lines in various sections of electric networks is one of the most important tasks for ensuring the reliability of electricity supply to consumers, which is implemented through the development and implementation of specialized information and measurement systems (IMS) as a component of Smart Grid systems [5, 6]. The urgency of implementing such systems is due to the fact that the occurrence of emergency situations leads to disruption of the normal power supply of consumers associated with interruptions in power supply, as well as a decrease in the quality of electric energy. In turn, the deterioration of the quality of electrical energy can lead to the failure of equipment of electrical networks and consumers. The effective solution of this problem gives a significant economic effect due to the reduction of interruptions in electricity supply, the reduction of transport costs for bypassing the PL and KL, minimizing the total time of organizing repair and restoration works [2]. An effective way for time to cut of searching for a power line damaged section fault indicators with organized as network is to use [6–10]. Fault indicators it's devices for monitor the electromagnetic field around the power transmission line and record the fact of damage to the line.

The use of damage indicators is most relevant for distribution networks from 10 kV to 110 kV [6]. The main characteristic of these networks is their long length, which is due to a significant number of branches and the presence of areas with difficult access to routes such as overhead and cable lines. During the elimination of emergency situations in distribution electric networks, in particular, during the elimination of accidents associated with the failure of power transmission lines as a result of hostile actions, timely identification of the damaged section of the network acquires primary importance. Detection of a damaged section of the network and in most cases consists in finding the optimal way to bypass all nodes of the topological graph (in the case of overhead power lines bypass all sections of the line [6,7,11,12]. In case of damage in the most remote area [13], it is necessary to ensure inspection of the line along its entire length [6].

Therefore, determining the places of occurrence of an emergency situation, the reason that led to its occurrence and the development of measures to eliminate it is a complex and complex problem, the solution of which has become a daily operational task of dispatching services of electrical networks and systems.

The paper *aim* is to analyse the ways of increasing the reliability of electricity supply to consumers and the effectiveness of restoring electricity supply by operators of distribution systems, by developing a structure of means of identifying emergency conditions in distribution electric networks of IPS of Ukraine [14].

2. Materials and method

The construction of information and measurement systems (IMS) with primary transducers based on indicators with means of communication and information transmission reduces the time of searching for an accident to a minimum. When damage occurs, all indicators installed in the damaged areas between the data center and the damage site will send response signals to the dispatch center, which allows you to immediately determine the emergency zone and take immediate action.

In this case, the basis of the IMS is the measuring transducers that ensure the determination of emergency mode parameters. In the electrical networks of European countries, damage indicators have been found widely used as measuring transducers (measuring operational parameters in electrical networks) [12, 15]. The use of damage indicators in the structure of the IMS. So compatible with the means of pre-processing, communication and information transmission, allows to reduce the time to eliminate the cause of the emergency situation to a minimum, which allows immediate identification of the emergency area and the implementation of operational actionist of the research.

Damage indicators, which have found application in electrical distribution networks, are based on different principles of operation. The simplest option of damage indicators are devices that record the exceeding of a certain short-circuit current threshold by the measuring transformer. The distance to the emergency site is determined based on the known calculation parameters of the network, namely the voltage values in the network and the value of the transient resistance at the point of damage. Usually, the indicated indicators for determining the distance to the place of damage on the distribution lines are ineffective due to several branches, which is due to the small values of the short-circuit currents and the length of the electrical networks. This problem is solved by installing damage indicators at the beginning of the branches of each line. In this case, by combining information about the distance to the accident site with information from damage indicators, the exact location of the damaged section of the network is obtained. The disadvantages of such devices are the need for additional calculations and the use of an electromagnetic type measuring transformer. The use of a measuring transformer in many cases is associated with difficulties in their implementation and ensuring operation in the conditions of a continental climate on the territory of Ukraine. Which is characterized by hot summers and frosty winters with significant temperature drops. Information and measurement systems with optical indicators of damage do not have this drawback [16]. The principle of operation of optical indicators is based on the use of electro- and magneto-optical effects. The use of the stability of the manifestation of the physical effect of the influence of magnetic or electric fields, which arise under the action of the measured current or voltage on the parameter of optical radiation, allows to ensure high accuracy of measuring currents and voltages. The conversion of the measured electrical values into the parameter of optical radiation takes place directly in the high voltage zone, then, using optical communication channels, the measurement information from the high voltage zone is transmitted to the low-voltage part of the IMS located in the safe zone. A directly measurable value when using electro- and magneto-optical effects is the parameter of optical radiation, the measurement of which can be carried out with high accuracy [17]. The obtained results do not depend on external meteorological factors. The main advantage of optical damage indicators is a wide signal bandwidth, high resistance to interference, durability, stability and simplicity of the optical element, as well as the ability to determine very short values of short-circuit currents in the millisecond range [7]. Such values of short-circuit currents occur in cases of short-circuit to the ground, for example, during the occurrence of a short-circuit of a phase to the ground or to a neutral wire under the influence of natural elements. A significant disadvantage of optical damage indicators is the high cost of optical damage indicators, which is due to a number of reasons [18]:

- the high cost of the manufacturing technology of optical elements and means of measuring their output values;
- insignificant power of the output circuits, which is insufficient to activate the existing sets of electromechanical protections, and the need to use additional hardware to increase it;
- lack of protection terminals and metering devices produced by domestic and many foreign manufacturers, corresponding inputs for connecting optical converters;
- lack of national standards that regulate the verification and determination of the accuracy

class of optical sensors and transducers in general;
- lack of sufficient statistical data on the use of these devices, which makes it much more difficult to determine their reliability;
- the high cost of projects due to the high cost of converting devices and network equipment, as well as the organization of current and voltage circuits in digital form.

Since a significant number of advantages of optical damage indicators can be provided by traditional measuring current transformers, the most effective is the construction and use of fault indicators employ measurement of the magnetic field induced by the current in the current measuring transformer network. The working principle of fault indicators is based on: signal from the secondary winding of the measuring current transformer is proportional to the primary induced current and shifted relative to it by a phase angle close to zero.

Existing damage indicators based on the measuring current transformer, due to the peculiarities of their designs and ensuring the possibility of monitoring them during operation and minimizing measurement errors, are mostly installed only in large nodes of generation and distribution of electrical energy, such as stations and substations. Moreover, the measuring transformer is usually a component of closed and open distribution devices. In addition to the mentioned restrictions on the place of placement, their disadvantage is a long time of installation, adjustment and the need to remove voltage during their installation and maintenance.

3. Results

To ensure the creation of a damage indicator, which allows you to reduce the time of searching for the cause and the place of occurrence of an emergency situation to a minimum, as well as to ensure connection to operating overhead and cable lines without removing voltage by connecting the output of the secondary winding of the measuring current transformer of the detachable design to the measuring transformers -creators placed directly near the measuring current transformer with the help of a mechanical spring mount. The connection diagram of the current transformer is shown in figure 1, which shows: the load current sensor (LCS) and the measuring system (MS). The IMS contains: a non-invasive current sensor, which consists of an inductive current transformer with a collapsible core (1), a resistor designed to convert the current value into a voltage (2), a shift reference voltage stabilizer implemented on analog elements (3). The system contains: an ATmega328 microcontroller (4), an interface converter chip (5), a 2x16 character liquid crystal display (6) to ensure the display of information in case of need, an LED (9) intended for global indication of a normal and emergency situation on the power line. LCS and VS, together with a personal computer (7) or other specialized means of information processing, on which specialized software is installed, form the IMS of control and monitoring of emergency parameter s of power transmission lines in distributed electric networks. The personal computer (7) is located in the control center in the case of remote access to the IMS or in the immediate vicinity of the IMS in a safe area.

The data collected from the measuring transducers of the LCN indicators are transmitted to the network part of the IMS. Using the obtained data with the help of unit 7, it is possible to monitor the magnitude of the electric current, to recognize the reason for the sudden increase in current strength: the connection of a new load or the appearance of a short-circuit current, and when conducting additional coefficients, to determine the approximate amount of consumed (released) electricity in the sector – divided network and easy to adjust taking into account possible peak loads in branched. Each indicator is equipped with LED 9 to provide a visual indication of the state of the lines, in the case of normal operation of the line, the LED continuously lights up in green color, in the event of an emergency, the LED switches to the red code glow mode. The type of code glow is determined by the type of emergency on the line.

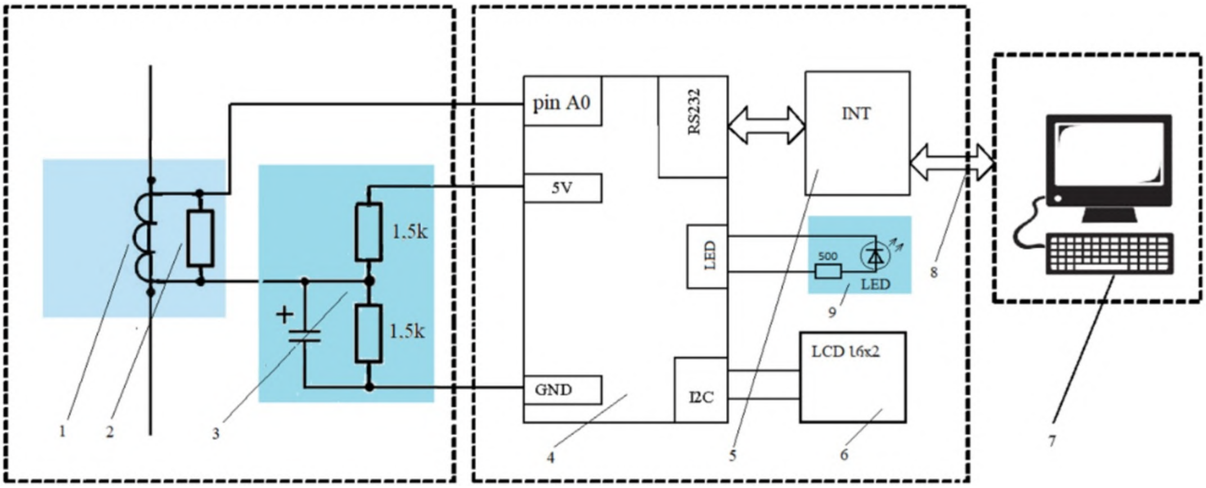

Figure 1. Block diagram.

The use of LCS indicators, which have means of communication and information transmission (units 5 and 8), ensure that the time for searching for an accident is reduced to a minimum. In the event of damage, the LCS indicators installed on the damaged areas and send appropriate signals from place of damage to the dispatch center, which allows immediate identification of the emergency area and immediate action to eliminate the emergency situation.

In order to verify the results of the research on the components of the system of the intellectualized emergency meter for the identification of damage to overhead and cable lines, test and demonstration stand was created, the photo of which is shown in figure 2.

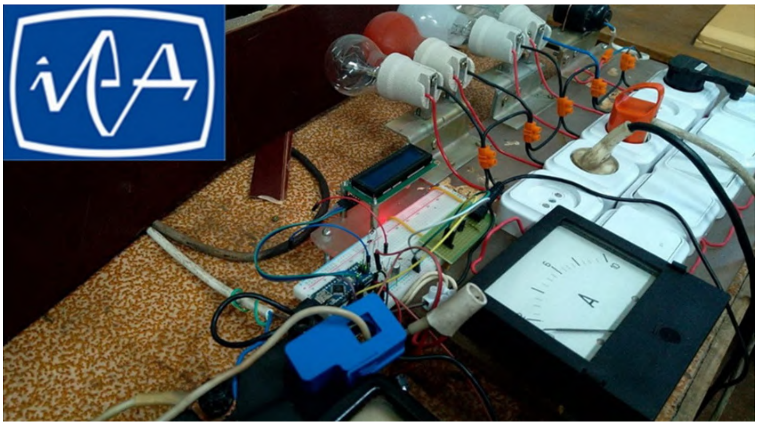

Figure 2. Test and demonstration stand.

The test was carried out by the method of direct comparison with an exemplary meter of the information component. The ProsKit MT-1270 device with an accuracy class of 0.5 for determining the current value and an ammeter E59 with an accuracy class of 0.5 were used as sample meters. The obtained measurement results are shown in figure 3.

The obtained results (figure 3) confirm the functionality of the intellectualized emergency condition meter for distribution electrical networks in a single-phase cable network with a collapsible core.

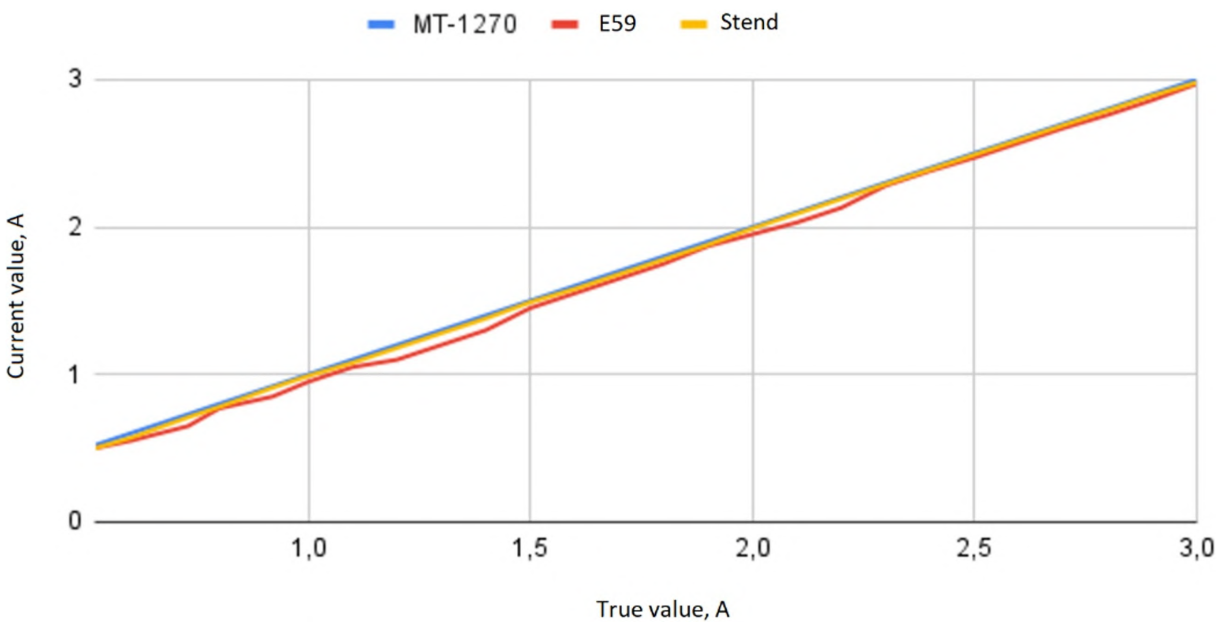

Figure 3. Research results.

4. Conclusions

Fault indicators are used to determine different types of damage in cable and overhead lines of electrical networks of different voltage classes, allow visual indication of the damaged section of the line, and in the case of the presence of a suitable interface, transmit this data remotely. Schematic and technical solution for the construction of damage indicators makes it possible to ensure connection to operating overhead and cable lines without removing voltage, and also, unlike existing damage indicators, due to additional coefficients, to determine the estimated amount of consumed (released) electricity in the sector of the distributed network and to easily adjust taking into account possible peak loads in the branch.

The development and implementation of such indicators is the basis for the construction of specialized information and measurement systems in electrical networks, the use of which reduces transport costs during the search for places of damage, minimizes the total time of organizing restoration and repair works, which in turn allows to increase electricity supply reliability to consumers and receive a positive economic effect by reducing of interruptions in their energy supply.

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References

[1] Kyrylenko O V 2016 *Intelligent electrical networks: elements and modes* 400 (Institute of Electrodynamics of the National Academy of Sciences of Ukraine)
[2] Blinov I, Zaitsev I, Parus E and Bereznychenko V 2023 Faults Indicators Applying for Smart Monitoring System for Improving Reliability Electric Power Distribution *Power Systems Research and Operation: Selected Problems II* ed Kyrylenko O, Denysiuk S, Derevianko D, Blinov I, Zaitsev I and Zaporozhets A

(Cham: Springer International Publishing) pp 235–256 ISBN 978-3-031-17554-1 URL https://doi.org/10.1007/978-3-031-17554-1_11

[3] Worighi I, Maach A and Hafid A 2015 Modeling a smart grid using objects interaction *2015 3rd International Renewable and Sustainable Energy Conference (IRSEC)* pp 1–6 URL https://doi.org/10.1109/IRSEC.2015.7454968

[4] Łowczowski K and Olejnik B 2022 *Energies* **15**(3) 1066 ISSN 1996-1073 URL https://doi.org/10.3390/en15031066

[5] Henriques H and Mestrando R C 2018 Use of smart grids to monitor technical losses to improve non-technical losses estimation *2018 Simposio Brasileiro de Sistemas Eletricos (SBSE)* pp 1–6 URL https://doi.org/10.1109/SBSE.2018.8395924

[6] Blinov I, Zaitsev I, Parus Y and Bereznychenko V 2022 Analysis of the Effectiveness Fault Indicators use for Control Overhead Power Lines *2022 IEEE 8th International Conference on Energy Smart Systems (ESS)* pp 17–20 URL https://doi.org/10.1109/ESS57819.2022.9969272

[7] Ho C Y, Lee T E and Lin C H 2011 *IEEE Transactions on Power Systems* **26**(1) 38–45 URL https://doi.org/10.1109/TPWRS.2010.2048725

[8] Shahsavari A, Mazhari S M, Fereidunian A and Lesani H 2014 *IEEE Transactions on Power Systems* **29**(5) 2359–2369 URL https://doi.org/10.1109/TPWRS.2014.2303933

[9] Teng J H, Huang W H and Luan S W 2014 *IEEE Transactions on Power Systems* **29**(4) 1653–1662 URL https://doi.org/10.1109/TPWRS.2013.2294338

[10] Usida W F, Coury D V, Flauzino R A and da Silva I N 2012 *IEEE Transactions on Power Systems* **27**(4) 1841–1849 URL https://doi.org/10.1109/TPWRS.2012.2190625

[11] Jahedi A, Javidan J and H N 2014 *International Journal on "Technical and Physical Problems of Engineering"* **6**(21) 106–111 ISSN 2077-3528 URL http://web.archive.org/web/20170829061723if_/http://www.iotpe.com/IJTPE/IJTPE-2014/IJTPE-Issue21-Vol6-No4-Dec2014/19-IJTPE-Issue21-Vol6-No4-Dec2014-pp106-111.pdf

[12] Masoud A and Navid G 2014 *World Applied Programming* **4**(8) 181–192

[13] Edmonds J and Johnson E L 1973 *Mathematical Programming* **5**(1) 88–124 ISSN 1436-4646 URL https://doi.org/10.1007/BF01580113

[14] Böttcher P C, Rydin Gorjão L, Beck C, Jumar R, Maass H, Hagenmeyer V, Witthaut D and Schäfer B 2023 *Energy Adv.* **2**(1) 91–97 URL http://dx.doi.org/10.1039/D2YA00150K

[15] Roberts J, Altuve H and Hou D 2001 *Review of ground fault protection methods for grounded, ungrounded and compensated distribution systems* (SEL) URL https://selinc.com/api/download/2604

[16] Listyuhin V A, Pecherskaya E A, Timokhina O A and Smogunov V V 2021 *Journal of Physics: Conference Series* **2086**(1) 012059 URL https://doi.org/10.1088/1742-6596/2086/1/012059

[17] Schon K 2019 Electro-optic and Magneto-optic Sensors *High Voltage Measurement Techniques: Fundamentals, Measuring Instruments, and Measuring Methods* (Cham: Springer International Publishing) pp 201–221 ISBN 978-3-030-21770-9 URL https://doi.org/10.1007/978-3-030-21770-9_6

[18] Tankevich S 2011 *Adaptive measuring converters of current and voltage for high-voltage electric power facilities* Ph.D. thesis Institute of Electrodynamics of the National Academy of Sciences of Ukraine

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Energy efficient computing by using of software optimization aimed on execution time

Energy efficient computing by using of software optimization aimed on execution time

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Abstract. Despite of all hardware capabilities, optimization of software always was one of actual tasks. Usually optimization of software was aimed to reduce an execution time. But recent decades it's possible sometimes also to reduce energy consumption and/or energy efficiency of computing because of enhanced energy saving capabilities. Indeed, if computations are made faster, CPU can suspend unusual computational and control blocks. In case of parallelization which is one of optimization techniques, power consumption can raise in short periods of computations because of using multiple CPUs simultaneously. At once execution time can be decreased dramatically so energy efficiency of computing still increasing. In the paper the authors provide the experiments on small size mini PC Raspberry Pi 3B which show that using of optimization tiling method not only speed up a processing but also increase energy efficiency of computing. For such low power systems this can be useful to increase power on time with a battery power source.

1. Introduction

The problems of computer systems power consumption have been taking attention for a long time. There were several reasons for this. First, a requirement to increase computing performance has increased the number and activity of nodes in computer systems. Second reason is a development of a different purpose computing system such as stand-alone computing units, mobile devices or on-board computers. Development and research of embedded computing systems have brought particular attention to energy use issues [1]. The third reason worth mentioning is a development of systems based on multiprocessor computing systems, such as network servers, data centers, multi-machine complexes for high-performance computing demands. The feature of this class of systems is a requirement to organize a special infrastructure with support for sustainable power, cooling, etc.

Andrae and Edler [2] show various projected scenarios of data centers power consumption by 2030. On the basis of this increase in power consumption by data centers and structure of this demand, it can be concluded that a comprehensive approach has to be taken to address the problem of reducing electricity consumption in this sector. In addition to measures to reduce computing costs, solutions to reduce energy consumption by data center infrastructure should be implemented. This is true for both high-performance computing and global information networks.

Ciancarini et al [3] showed that activities in various sectors of economics are increasingly being digitized. Human activities are increasingly dependent on information technology, resulting in increased energy consumption. Usage of smartphones, tablets and other mobile devices significantly expands a number of active users.

Gupta and Singh [4] shows the power consumption structure of a personal computer including printer and communication system. The authors presented a technical overview of minimization methods of energy consumption by computer systems. Based on the methods of calculation of energy consumption using hardware, software, processor and various algorithmic approaches, a conclusion is presented that there is a great need to change of operating system work at moments of inactivity. Available options in power circuits of computers and peripherals are based on a timeout approach. This is not enough to solve the problem of minimization of energy consumption.

Szydlowski and Chvála, Jr [5] give a fairly detailed study of power consumption of personal computers and workstations. The study should be taken into account, even though the data may appear to be outdated at first glance due to evolving technologies. With a load of 75 to 175W standard PC consumed 144 W, and standard workstation takes 173W. Peripheral equipment such as printers and modems accounted for only 16% of the total workstation consumption. This information indicates that energy-saving measures should focus on computers (50% of total consumption) and monitors (35% of total consumption). Laser printers at 12% of total workstation consumption, also require attention because they are involved in the work, usually 24 h/day. The paper presents a problem of software optimization as a component of the complex solution for the problem of reduction of energy consumption. A focus of the research is on solutions for design and use of mobile and embedded systems. There is an additional point for research in a field of energy efficiency of devices.

An issue of increasing energy consumption has affected on field of mobile information technologies. A growth of energy consumption has outpaced of development of energy storage technologies, in particular, a capacity of batteries. This is reflected in a significant reduction in a lifetime of mobile device batteries while increasing their functionality. Thus, the challenge of improving the energy efficiency of information technology is not only to save energy, but also to extend the battery life of mobile devices.

Hassan et al [6] shows a dependence of a performance and energy consumption of computer systems on quality of program code. The authors demonstrated that in order to ensure the best performance indicators for computer systems, there is a balance between performance, capacity and energy consumption and a choice of a right coding style together with “right” compiler determines an achievement of this balance.

In this article, the approach of the authors is defined by three provisions. First, in a transistor gate in general, two types of power dissipation can be distinguished: static and dynamic. Static power dissipation is measured in opened or closed states of transistor switch. Dynamic losses occur during transistor switching from one state to another. Dynamic losses account for up to 80% of total digital circuits power dissipation. Second, when analyzing of algorithms of computing systems, it is clear that most of computational time of software happens to a cyclic loops of algorithms. By improving of cyclic loops or sections, it is possible to reduce an activity of electronic components and, accordingly, dynamic losses of digital circuits. And third, algorithm transformations should be done at system level. This provides a significant benefit in terms of reducing the impact of poor program source code on a performance of computer system. So, the main idea of the author’s approach is to make transformation of program sources taking into account program loop operators and making source-to-source transformation.

Further, in the first section the authors present modern methods and approaches used in the optimization of computer programs. The next section provides hardware and software tools for estimation of execution time of initial and optimized test programs. The results of the optimization method of tiling and parallelization, which show the change in the performance and energy efficiency of calculations, are given in the latest section.

2. Motivation

From the very beginning of computational systems' development, a lot of efforts were spent to make hardware smaller and to consume less power. Such methods as dynamic clock rate, unused block hibernation, lower operation voltage, comprehensive electric layers' design were used and also are used now to reduce power consumption.

At the moment most of electronic components are built by using complementary metal-oxide semiconductor (CMOS) technology. This technology was discovered by different authors [7, 8] and all effects which lead to higher power consumption are known. All sources of CMOS digital circuits power dissipation can be divided onto 4 groups.

(i) Short-circuit current
(ii) Parasitic leakage current
(iii) Static dissipation
(iv) Dynamic dissipation

Dynamic dissipation is a main dealer of power dissipation and it can dissipate up to 80% of total energy dissipation [9]. Formula for dynamic power dissipation is depicted below:

$$P_{dynamic} = C \cdot V^2 \cdot k \cdot f, \tag{1}$$

where C is a total capacity of a circuit, V – voltage span, k – activity factor and f – switching frequency. Dynamic dissipation take place when a circuit switches from one digital state to another. Dynamic dissipation is linear to switching frequency. If there is no switching – dynamic power will be absent. More active elements involved – higher dynamic dissipation occurs [10].

In terms of software optimization, it can be concluded that every method which reduces register or memory usage or functional blocks is involved as well, in theory can reduce dynamic dissipation. Software optimization methods are aimed on different software parameters. Often main goal of optimization is a reducing of time execution of program. It allows to perform computational tasks faster or to increase a functionality of a software by adding new features to it which were not possible with slow computations. Most of execution time software spends in computational loops which perform the same computational operations for different data. Improvement of any single operation will lead to improvement of every computation in it. Thus, optimization methods targeted on execution time are developed to implement them in computational loops. Some of software optimization methods are listed below.

- fission/distribution;
- fusion/combining;
- interchange/permutation;
- inversion;
- loop-invariant code motion;
- parallelization;
- reversal;
- scheduling;
- skewing;
- splitting/peeling;
- software pipelining;
- tiling/blocking;
- unrolling.

Mentioned methods provide different approaches to speed up a computational loop. Some of them are intuitively clear like parallelization when data are distributed between CPUs for faster execution. Some methods are not so clear. For example, tiling method, practical usage of which will be discovered below, is not so evident. For mathematical description and handling of different optimization methods several models were proposed. One of most used is a polyhedral model [11]. This model represents a loop or loop nest as a defined mathematical abstraction [12]. Every loop is described with a set of inequalities and limits. Such approach allows to alter one or several loops by changing their parameters and convert model back to code. Polyhedral model can handle tiling method. Tiling method is an optimization method which divides iteration space onto smaller parts named tiles. Computation of data on smaller range provides better data locality and less cache misses. This can lead to faster execution time. Another promising factor that during tiling usage a software natively obtains a different computational blocks which is possible to distribute on different CPUs if there are no data relations between them. Combining of tiling method and parallelization can have synergistic effect.

3. Hardware and software set

As it mentioned above, a lot of optimization methods are used to gain different improvements: faster execution time, lesser data or code memory usage etc. But what to do if desired goal of optimization is a lesser power consumption or better energy efficiency? How to change a software to reach it?

Because computational system is a comprehensive set of many hardware sub-parts which consume energy, there is no single target parameter available in code to optimize. A possibility that some optimization methods can to influence on energy consumption should be discovered.

The authors performed several experiments to verify it. First, software optimization method should be chosen. The authors have chosen tiling method which uses polyhedral model as a mathematical description. Main idea of the method is to reduce iteration space onto smaller parts which are called tiles (figure 1). It produces better usage of cache memory and improves data locality. Also, to reveal a power of multi-core CPU a parallelization method was used in addition.

Usually, an optimization is performed by compiler or manually. There is another way to

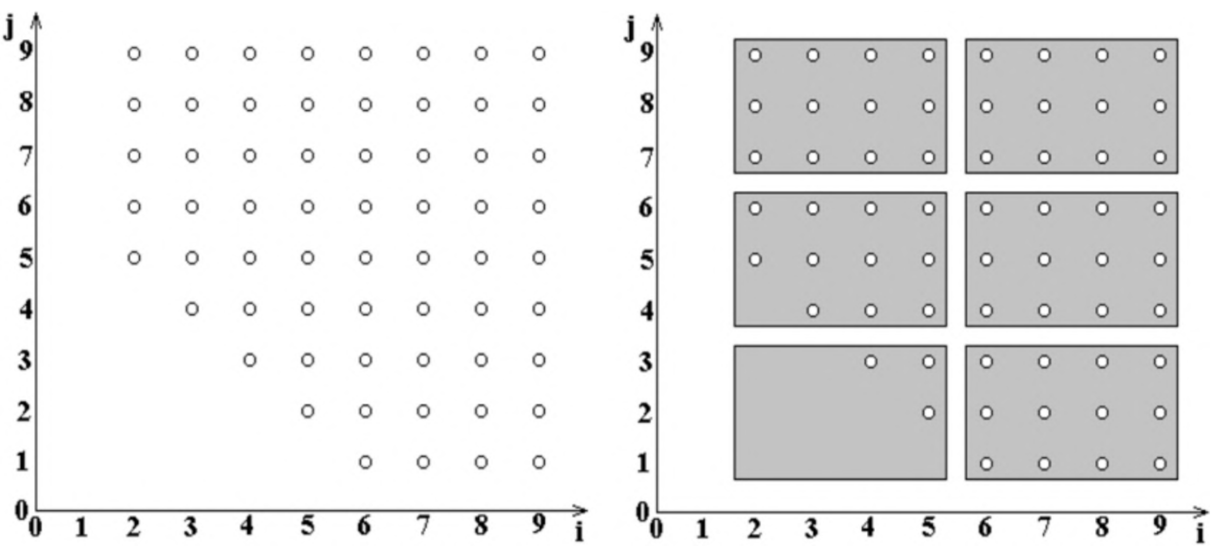

Figure 1. Example of original and tiled iteration spaces. Obtained tiles are selected in gray rectangles.

optimize source code without using compiler's features.

To apply tiling method, the authors used Pluto framework [13]. This is a set of tools which automatically can apply several tiling methods and parallelization as well. This is achieved by transformation of C source code to another source code by some rules. After it a new code should be compiled as usual. Such code-to-code transformation allows researchers and developers to be focused and to improve specific optimization methods. No changes to compiler are required. Moreover, all compiler's optimization methods also are applied on a stage of compilation.

Next, to verify any optimization some test applications are required. In common case, any optimization aimed to execution time reduction or energy consumption can be only verified on real execution of software. The authors chosen Polybench [14] set of test applications. It includes about 30 tests of linear algebra, simulation, vector and matrix computations. The tests have embedded tools to measure execution time. By altering the tests by source-to-source transformation and to compile and execute a new code it's possible to measure and compare new execution time.

Finally, a Raspberry Pi 3B board was chosen as a hardware platform for tests (figure 2). This credit size mini PC has 4 ARM based CPUs, 1 GB of RAM, video, audio outputs and general purpose input/output signals (GPIO). This PC can operate on Linux based distributives and usually is chosen for home automation, home or NAS server and IoT. Figure 2 (b) also shows the Raspberry Pi hardware structure.

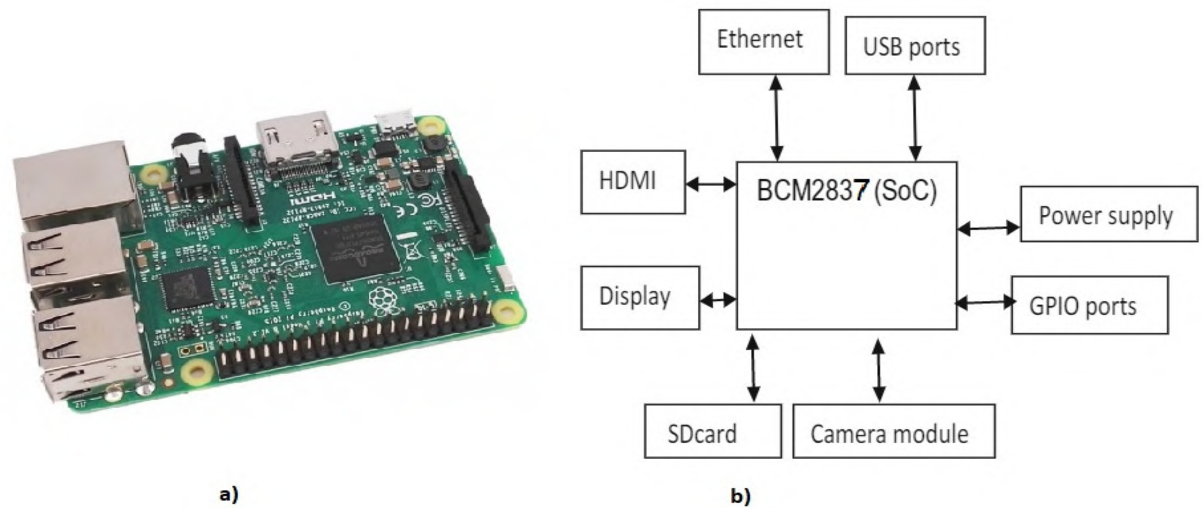

Figure 2. Raspberry Pi 3B mini computer (a) and its hardware structure (b).

Main idea of the tests is to measure a speedup of execution time, energy consumption and to calculate energy efficiency of optimized tests.

4. Experiments

To evaluate an energy efficiency, it is not enough to measure only execution time. Because an optimized software can use less or more electric power i.e. in case of multi-core optimization and be faster or slower an electrical power consumption also should be taken into account. Energy which is required to compute any result is an integral of electric power on time or, in simplified form, when exact power consumption in time is not known, equals to a multiplication of average power by time of computation:

$$E = P \cdot T, \tag{2}$$

where P is an average power consumption, T – execution time. To estimate energy efficiency coefficient for non-optimized and optimized version it's necessary to compare required energy in both cases. When required energy is lower than before then coefficient of energy efficiency will be more than 1, if higher – then less than 1. If to apply previous formula, we can obtain:

$$K_E = \frac{E_{original}}{E_{optimized}} = \frac{T_{original}}{T_{optimized}} \cdot \frac{P_{original}}{P_{optimized}}, \tag{3}$$

To evaluate an energy efficiency coefficients two measurements were made. First measurement was a measurement of execution time and second one was a measurement of average power consumption. Both measurements were made for non-optimized and all versions of optimized test programs. Optimized version was made with different tiling options of Pluto software. After applying of formula above were obtained energy efficiency coefficients which were composed in table 1.

As it follows from the table, different coefficients of energy efficiency were obtained. For better readability the data are shown on figure 3. There are test programs on the horizontal axe. On the vertical axe there is a coefficient of energy efficiency. For non-optimized program it's always 1. The different optimization methods are depicted by the different color lines. Some of optimization methods are only a variation of tiling method but also some of them are combined with parallelization. In that case name “parallel” is presented inside its name.

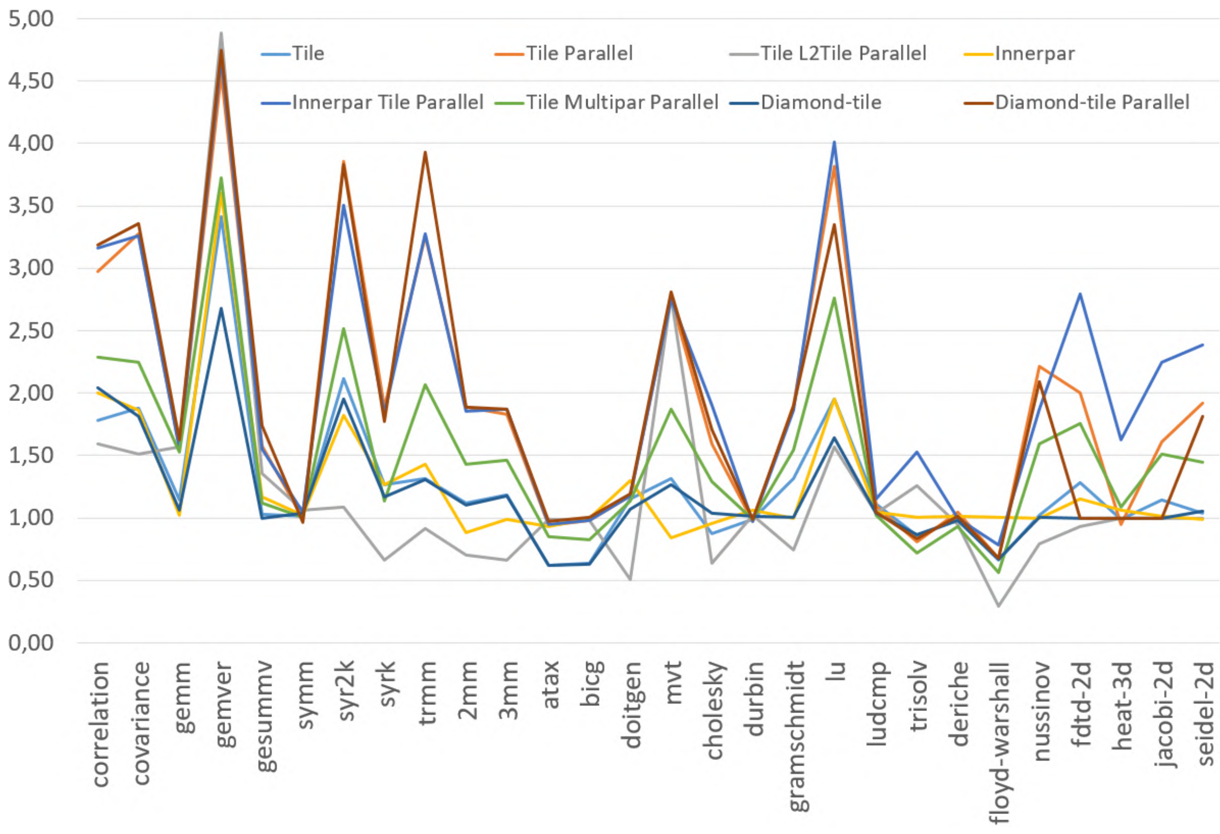

Figure 3. Coefficients of energy efficiency for different test programs and optimization methods.

If to look onto the plot it can be recognized that some of the optimization have much better results than other. Often this is a blue and red lines which mean “Tile Parallel” and “Innerpar Tile Parallel” methods. Both of them have parallelization option. It means that parallelization

Table 1. Coefficients of energy efficiency for Polybench tests on Raspberry Pi 3 board on different optimization methods, times.

Test	Tile	Tile Parallel	Tile L2Tile Parallel	Innerpar	Innerpar Parallel	Tile Multipar Parallel	Diamond-tile	Diamond-tile Parallel
correlation	1.78	2.97	1.59	2.00	3.16	2.29	2.04	3.18
covariance	1.88	3.27	1.51	1.87	3.26	2.25	1.81	3.35
gemm	1.14	1.56	1.57	1.02	1.56	1.53	1.06	1.63
gemver	3.41	4.56	4.88	3.60	4.69	3.72	2.68	4.75
gesummv	1.03	1.57	1.36	1.17	1.55	1.12	1.00	1.74
symm	1.01	0.99	1.06	1.02	1.05	1.01	1.04	0.96
syr2k	2.11	3.85	1.09	1.82	3.51	2.51	1.95	3.83
syrk	1.26	1.89	0.67	1.27	1.84	1.13	1.17	1.77
trmm	1.31	3.26	0.91	1.43	3.28	2.06	1.30	3.93
2mm	1.12	1.89	0.70	0.88	1.86	1.43	1.10	1.89
3mm	1.18	1.83	0.66	0.99	1.87	1.46	1.17	1.87
atax	0.62	0.94	0.98	0.93	0.95	0.85	0.62	0.98
bicg	0.64	0.98	0.98	1.00	0.98	0.82	0.63	1.01
doitgen	1.15	1.18	0.51	1.30	1.18	1.14	1.07	1.19
mvt	1.32	2.75	2.77	0.84	2.75	1.87	1.26	2.81
cholesky	0.87	1.60	0.63	0.95	1.91	1.29	1.04	1.71
durbin	0.99	0.97	1.02	1.06	0.97	0.99	1.01	0.99
gramschmidt	1.32	1.90	0.74	1.00	1.86	1.54	1.01	1.89
lu	1.95	3.82	1.57	1.95	4.01	2.76	1.64	3.35
ludcmp	1.11	1.09	1.04	1.04	1.15	1.02	1.04	1.04
trisolv	0.86	0.81	1.26	1.00	1.53	0.72	0.86	0.83
deriche	0.98	1.04	0.95	1.01	0.99	0.93	0.98	1.01
floyd-warshall	0.66	0.68	0.29	1.00	0.78	0.56	0.67	0.68
nussinov	1.02	2.22	0.79	1.00	1.87	1.59	1.00	2.09
fdtd-2d	1.28	2.00	0.93	1.15	2.79	1.76	0	0
heat-3d	0.99	0.95	0.00	1.06	1.62	1.09	0	0
jacobi-2d	1.14	1.61	0.00	1.01	2.24	1.51	0	0
seidel-2d	1.04	1.92	0.00	0.99	2.38	1.44	1.06	1.81

on Raspberry Pi 3B which has 4 cores works quite good and all CPUs share computational tasks in that cases.

As it follows from the figure, quite often it's possible to obtain an energy efficient coefficient more than 1. It means that optimized software requires less energy to compute the same algorithm. On other hand there are several algorithms which didn't receive any reducing of total required energy. For example, Floyd-Warshall algorithm which is an algorithm for finding the shortest path between all pairs of vertices in a weighted graph, didn't get better energy efficiency in any applied optimization method.

5. Conclusion

If to review the obtained results it should be concluded that optimization methods provide better energy efficiency in most cases. Usually, it's provided by significant speed up of execution time with slightly increased power consumption. Together these results produce better energy efficiency of computing. In some particular cases test program didn't react on optimization methods and in such cases energy efficiency was the same or even worse.

Big difference of energy efficiency on the different tests and different optimization methods shows that in any particular case optimization method should be chosen carefully. Several experiments should be done with different optimization methods. Also measurement for original non-optimized software should be done. If there is no speed up of execution time for several tiling methods, then no tiling methods will boost it. Another optimization method should be chosen.

The authors also performed such experiments on other hardware platforms with tiling methods. In common, CPU has bigger cache – bigger speed up of execution can be obtained.

To summarize all the tests, it's necessary to highlight that optimization of software can really improve energy efficiency of computing by reducing of CMOS circuit switches. It improves program locality and this reduces dynamic and thus total power dissipation.

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References

[1] Fornaciari W, Gubian P, Sciuto D and Silvano C 1998 *IEEE Transactions on Very Large Scale Integration (VLSI) Systems* **6**(2) 266–275 URL https://doi.org/10.1109/92.678887
[2] Andrae A S G and Edler T 2015 *Challenges* **6**(1) 117–157 ISSN 2078-1547 URL https://doi.org/10.3390/challe6010117
[3] Ciancarini P, Ergasheva S, Kholmatova Z, Kruglov A, Succi G, Vasquez X and Zuev E 2020 *Electronics* **9**(10) 1678 ISSN 2079-9292 URL https://doi.org/10.3390/electronics9101678
[4] Gupta P K and Singh G 2012 *International Journal of Information Technology and Computer Science (IJITCS)* **4**(10) 57–66 URL https://doi.org/10.5815/ijitcs.2012.10.07
[5] Szydlowski R F and Chvála, Jr W D 1994 Energy consumption of personal computer workstations Tech. Rep. PNL-9061 Pacific Northwest National Lab. (PNNL) URL https://doi.org/10.2172/10134947
[6] Hassan H H M, Moussa A S and Farag I 2017 *International Journal of Advanced Computer Science and Applications* **8**(12) URL https://doi.org/10.14569/IJACSA.2017.081217
[7] Ellis C S 2007 *Controlling Energy Demands in Mobile Computing Systems* Synthesis Lectures on Mobile & Pervasive Computing (San Rafael: Morgan & Claypool) URL https://doi.org/10.1007/978-3-031-02475-7
[8] Glökler T and Meyr H 2004 *Design of Energy-Efficient Application Specific Instruction Set Processors* (Dordrecht: Kluwer Academic Publishers) URL https://doi.org/10.1007/b105292
[9] Havinga P J M and Smit G J M 1997 *Low Power system Design techniques for mobile computers* (*CTIT Technical Report Series* no 97-32) (Netherlands: Centre for Telematics and Information Technology (CTIT)) URL https://ris.utwente.nl/ws/portalfiles/portal/47275318/energy.design_havinga.pdf
[10] Roy K and Prasad S C 2000 *Low-Power CMOS VLSI Circuit Design* (Wiley India) ISBN 9788126520237
[11] Feautrier P and Lengauer C 2011 Polyhedron Model *Encyclopedia of Parallel Computing* ed Padua D (Boston, MA: Springer US) pp 1581–1592 ISBN 978-0-387-09766-4 URL https://doi.org/10.1007/978-0-387-09766-4_502
[12] Clauss P and Loechner V 1996 Parametric analysis of polyhedral iteration spaces *Proceedings of International Conference on Application Specific Systems, Architectures and Processors: ASAP '96* pp 415–424 URL https://doi.org/10.1109/ASAP.1996.542833
[13] Bondhugula U, Hartono A, Ramanujam J and Sadayappan P 2008 *SIGPLAN Not.* **43**(6) 101–113 ISSN 0362-1340 URL https://doi.org/10.1145/1379022.1375595
[14] Pouchet L N 2016 PolyBench/C: the Polyhedral Benchmark suite URL https://www.cs.colostate.edu/~pouchet/software/polybench/

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Analysis of the dynamics of the development of alternative energy plants in terms of their connection to the power transmission networks

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Analysis of the dynamics of the development of alternative energy plants in terms of their connection to the power transmission networks

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Abstract. In this article, the author presents an original approach to analyzing the dynamics of power plants' development with renewable energy sources. This approach is based on the characteristics of their connection to (high-voltage or distribution) power transmission networks during both the pre-war and post-war periods. The article describes the impact of military aggression on the current status of power generation from alternative energy sources. The article not only suggests the main directions of post-war reconstruction but also defines approaches to developing regulatory mechanisms to promote the growth of renewable energy at the regional power system level of the United Energy System of Ukraine.

1. Introduction

Economy, energy, and ecology are areas that play a significant role in society. Energy is of great importance because it influences both the development of the economy and ecology. It determines, to a great extent, the economic potential of the state, the well-being of its population, and also has the most significant impact on the environment (all environmental problems directly or indirectly related to the production or use of energy).

In recent years, both in Ukraine and worldwide, there has been steady development of small or low-capacity power plants using renewable energy sources (RES), which gradually replace traditional methods of generation. According to data from the State Agency for Energy Efficiency and Energy Saving of Ukraine [1], the installed capacity of power generators from alternative energy sources increased by 9.5 from 2014 to 2021, as shown in figure 1.

However, after Russia's full-scale invasion, Ukraine's energy industry has faced difficult times. Some of the generation facilities and energy infrastructures have been damaged, destroyed, or are located in the occupied territories, including renewable energy generation facilities. After the war, the energy industry needs to be restored and significantly expanded. Therefore, it is crucial to find approaches and methods to support and develop RES producers in the war and post-war period.

There has been a hectic discussion in various professional circles about decentralizing the power system [2] in the context of post-war reconstruction reflections. The concept of decentralization includes measures to ensure reliable power supply to critical infrastructure objects, houses, etc. in case of damage to important objects of the power system.

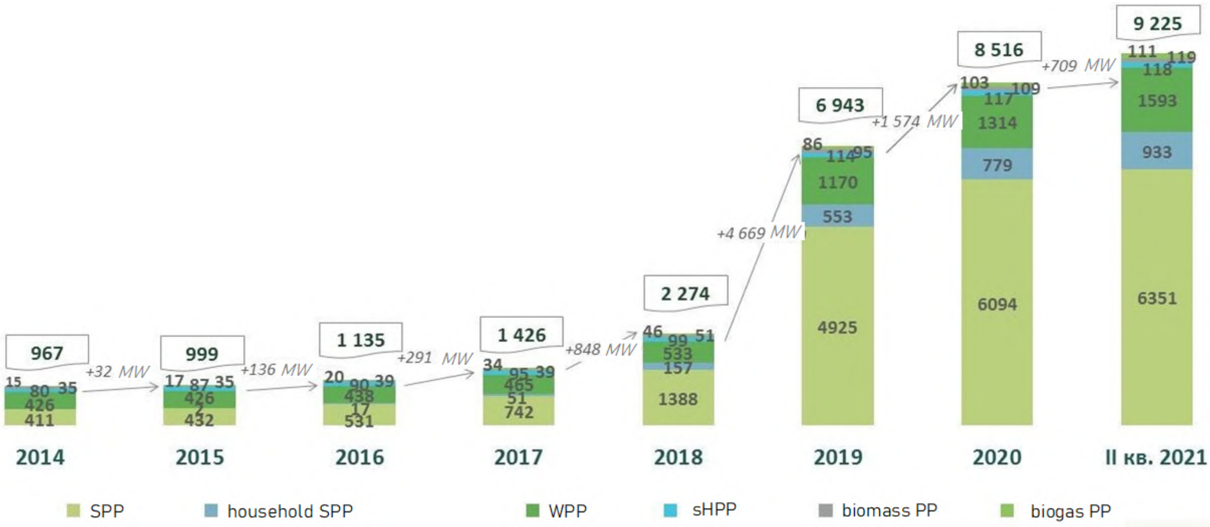

Figure 1. Installed capacity of renewable energy sources for 2014-2021 [1].

Distributed power generation is defined as an energy production and transmission system that involves a large number of consumers who, at the same time, are producers of electricity and heat for their own needs. They have the ability to transfer excess energy produced to the general power grid. According to the Law of Ukraine "On Electricity Market"distributed generation is defined as "a power plant with an installed capacity of 20 MW or less, connected to the electrical energy distribution system" [3].

To conduct research on the development of distributed generation in Ukraine and introduce new approaches and methods of supporting renewable energy in the war and post-war periods, it is essential to have data on the current state of renewable generation, as well as information on the capacities of RES facilities that are connected to the distribution network.

There are a number of scientific publications and information resources that analysed the dynamics of the development of alternative energy in Ukraine and the world. For example, the energy development strategy of Ukraine is reviewed in [4], the analysis of prospects for the development of renewable energy in Ukraine, the influence of military actions on the state of the industry, ways of development of RES in the post-war period, etc. are reflected in studies [5–11]. Also the analysis of using of renewable energy sources on the development of energy systems, using of "smart technologies"for renewable energy are shown in research [12–18]. However, none of them studies the state of alternative energy in terms of data on the connection of RES facilities to power transmission networks.

At the same time, in the research of Lukashevych and Evdokimov [19] describes the information system for monitoring the state and dynamics of development of RES power plants, its characteristics and structure. Besides, the described information system contains already formed and implemented in Excel data fields about RES objects of Ukraine, which should be used for the analysis of previous experience in development of power generation, its current state and formation of proposals for directions of post-war reconstruction.

The aim of the research is to analyze the dynamics of the development of alternative energy facilities in terms of their connection to power transmission networks.

The tasks of the study are:

- to determine the distribution structure of RES in terms of connection to the power grid in the pre-war period;
- to describe the impact of military aggression on the state of alternative power generation;

- to identify the approaches and methods of support and development of RES producers in the wartime and postwar periods.

2. Analysis of alternative generation in terms of connection to power transmission networks by 2022

The research [19] contains information about main RES facilities (name, address, type of source, amount of installed capacity of the facility), including data on the type of power transmission network to which the stations are connected – high-voltage or distribution. The data on the connection of individual renewable energy generation plants to the distribution or high-voltage comes from the analysis of all PPA contracts (Power Purchasing Agreements – long-term contracts for the purchase of electricity from renewable energy sources) signed by alternative energy producers with the state-owned company Guaranteed Buyer (SE "Guaranteed Buyer") from 2019 to 2022. However, the system does not yet include information on alternative generation facilities of households that have signed power purchase and sale agreements with universal service providers (USPs).

Based on the available information, we can perform an analysis of the dynamics of development of alternative energy facilities in terms of their connection to the high-voltage or distribution power transmission networks. The calculations were performed for operating plants (for power generation) that have a "green" tariff, without taking into account households that sell electricity to the USP.

Figure 2 shows the dynamics of the development of renewable energy producers for the period from 2019 to July 2022.

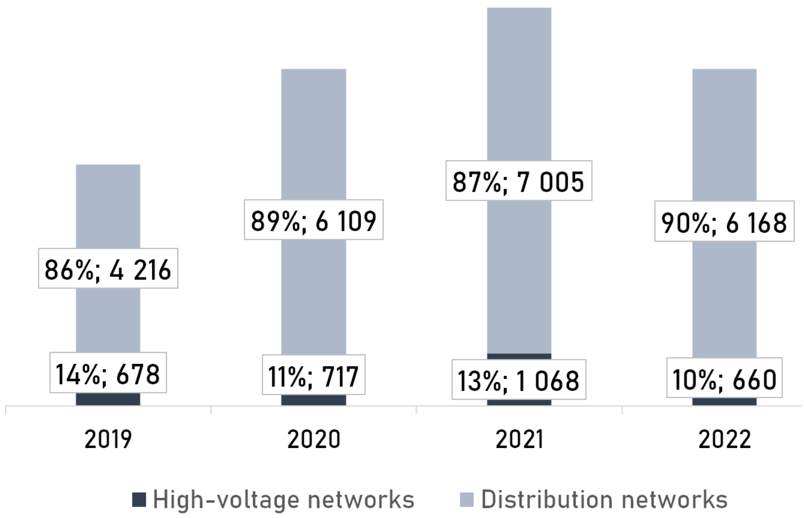

Figure 2. Distribution of installed capacities of operating alternative generation stations in terms of connection to power transmission networks for 2019-2022, MW.

The installed capacity of operating renewable energy production facilities increased from 4896 MW in 2019 to 8072 MW in 2021. However, due to military aggression in July 2022, only 6828 MW of operating capacity of alternative generation facilities remained in the unified energy system of Ukraine.

Also figure 2 illustrates the changing structure of RES producers in terms of their connection networks, with capacity connected to high-voltage networks increasing from 678 MW in 2019 to 1068 MW in 2021, and decreasing to 660 MW in July 2022. Correspondingly, capacity connected to distributed generation increased from 4261 MW in 2019 to 7005 MW in 2021, and decreased to 6168 MW in 2022. Thus, there is a trend towards the predominant connection of alternative generation plants to distribution grids, likely due to the low installed capacity of RES producers (with 98% of the total number of RES plants having an installed capacity of less than 50 MW) and the relative simplicity and cost-effectiveness of connecting to the distribution grid compared to the high-voltage grid.

Additionally, figure 2 shows that alternative generation peaked in 2021.

The distribution of installed capacities of operating alternative generation stations in 2021 is presented in figure 3.

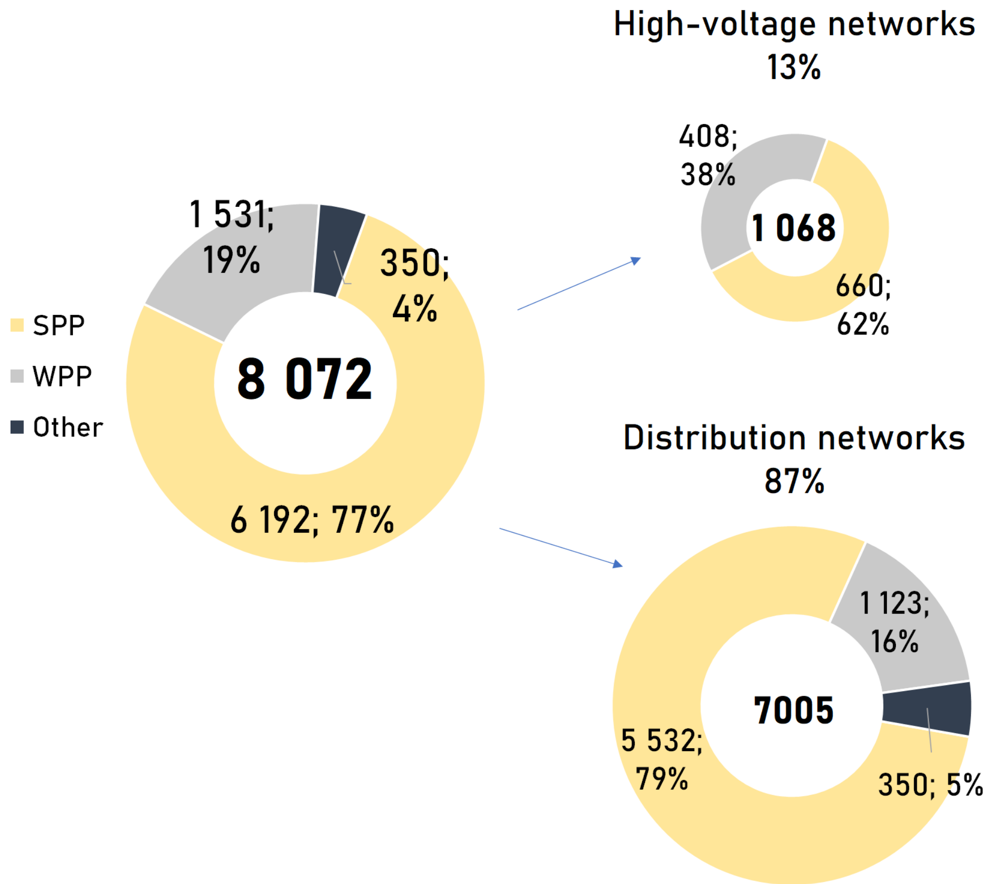

Figure 3. Distribution of installed capacities of operating alternative generation stations by sources of alternative energy and connection to power transmission networks in 2021, MW.

In 2021, 77% of total power generation came from solar power plants (SPP), 19% from wind power plants (WPP), and 4% from other power plants (small or micro hydropower plants; power plants using energy from biomass, gas from organic waste, sewage gas: biogas, etc.). 1068 MW or 13% of all alternative generation capacities were connected to the high-voltage grids, including 408 MW of wind power plants and 660 MW solar power plants. RES plants connected to the high-voltage networks were located in the Dnipro, Lviv, Mykolaiv, Kherson, and Khmelnytskyi regions, as shown in figure 4.

5532 MW of solar power plants, 1123 MW of wind power plants and 350 MW of plants generating electricity from other sources were connected to the distribution grid. These plants are distributed throughout the territory of Ukraine, taking into account the geographical and climatic conditions of the regions, as shown in figure 5.

Figure 4. Distribution of installed capacities of operating stations of alternative generation connected to high-voltage networks in 2021.

Thus, the development of solar energy can be observed practically on the entire territory of Ukraine, with the predominance of central and southern regions, wind power generation mainly in the south, small or low-power hydroelectric plants along riverbeds in the northwestern, central and eastern regions, and power plants using energy from biomass or biogas throughout the country. Separately, it is worth noting the relatively low development of RES in the northern and eastern regions of Ukraine.

In general, in 2021, the share of electricity generated from RES in Ukraine's energy balance was 12.8 TWh or 8%, of which 56% was generated by solar radiation, 33% by wind energy, almost 8% by biomass and biogas combustion, and 3% by small hydropower [20].

3. Analysis of the impact of military operations on alternative sources producers

In 2022, as a result of the military invasion, some of the alternative generation facilities were destroyed, damaged, or landed in occupied territories. Thus, the vast majority of renewable energy facilities currently installed in the country are located in the southern and southeastern regions of Ukraine, where active combat operations have being taken place in the last six months. According to various expert estimates, as of August 2022, 30-40% of RES in these regions has already been affected in one way or another [20].

For example, according to the Ukrainian Wind Energy Association, more than three-quarters of Ukraine's wind energy capacity has been shut down since the war began, and five wind turbines in the Kherson region installed at the wind farms in Myrne, Siva, and Novotroitsky have been destroyed now. Due to the damage of 330 kW of power transmission lines in Melitopol, almost 600 MW of wind power capacities in Zaporizhzhya region are also out of service. More than 1 MW of bioenergy capacity in Chernihiv was damaged, while bioenergy plants with total capacity of 2 MW are located in occupied areas of Donetsk region, namely in Volnovakha and Mariupol.

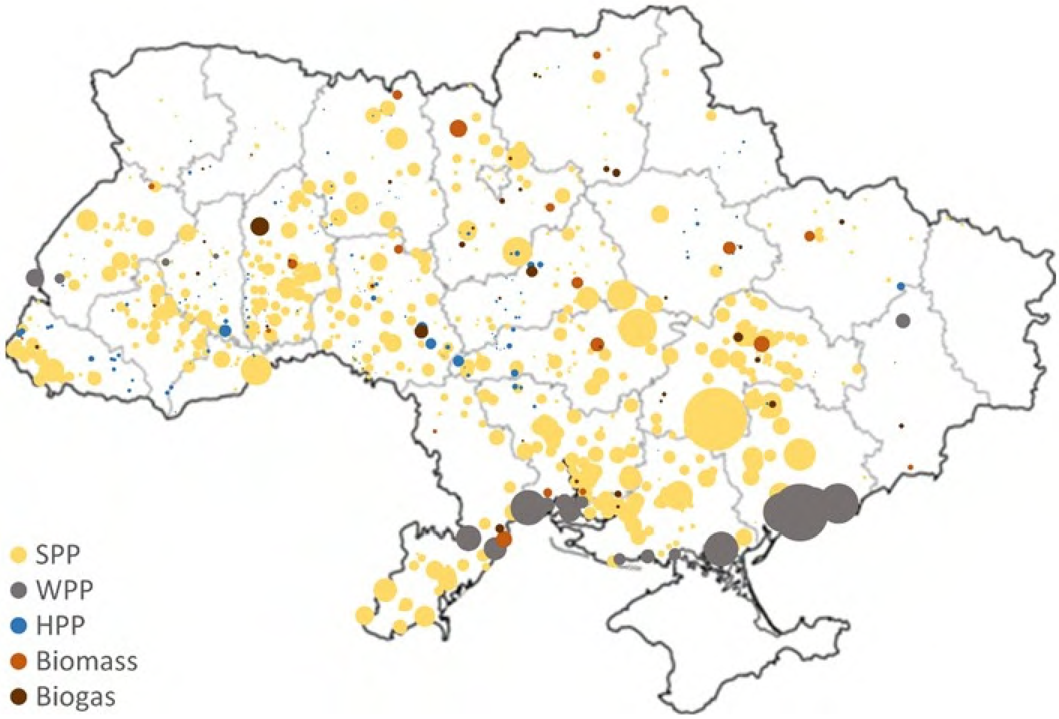

Figure 5. Distribution of installed capacities of operating alternative generation stations connected to distribution networks in 2021.

Fortunately, the small hydroelectric power plants, located mainly in the western regions of Ukraine, were not affected by the hostilities and continue to supply electricity [20].

As shown in figure 6, as of July 2022, 6828 MW of operating stations were connected to the United Energy System of Ukraine, of which 88% were SPPs, 7% were WPPs, and 5% were energy stations generating electricity from other sources. 660 MW of solar power plants in Dnipro, Lviv, Mykolaiv, and Khmelnytsky regions remained connected to the high-voltage network, which makes up 10% of all capacities of RES producers. The structure of stations connected to distribution networks is as follows: 5358 MW – SPPs, 476 MW – WPPs, and 334 MW – others.

Overall, wind and solar power generation has declined by more than half from pre-war levels. The following factors may serve as explanations: first, the destruction of power generation as a result of direct hostilities; second, the increasing problems related to the destruction of demand and the high inflexibility of power generation, especially solar power generation, considering that the cumulative capacity of solar power generation has currently exceeded 6 GW; and third, problems related to damage to energy infrastructure – networks, substations, etc. – will increase.

At the same time, the financial crisis in the RES market is deepening and the percentage of payment under the "green"tariff is decreasing. According to SE "Guaranteed Buyer" – as of December 26th, 2022 – the overall level of settlements with RES producers for the supplied electricity in 2021 was 99%, while in 2022 this indicator is 53.5% [21].

4. The directions of the post-war reconstruction of the RES producers

Renewable energy is one of the components of Ukraine's energy independence. Their potential can be used to create new jobs, boost the economic activity of regions, and renew outdated main production facilities in the power industry. Currently, the only mechanism to promote the development of RES in Ukraine is the "green"tariff – a special tariff for the purchase of

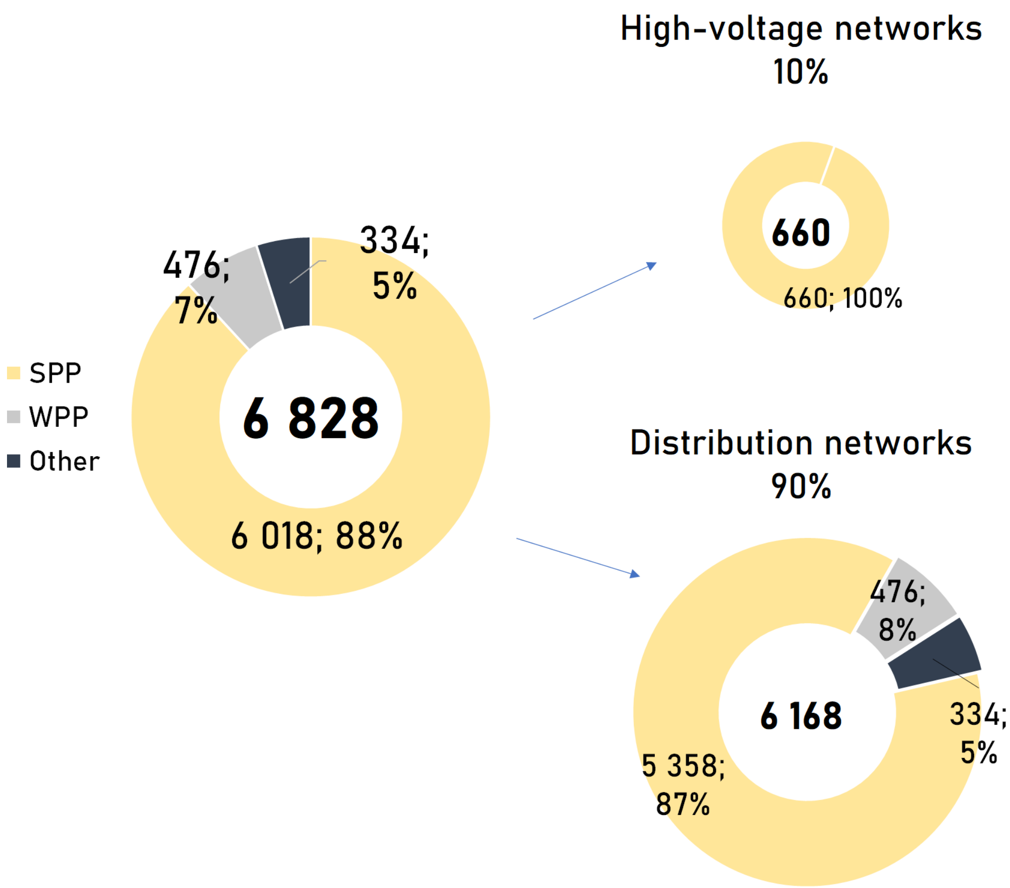

Figure 6. Distribution of installed capacities of operating alternative generation stations by sources of alternative energy and connection to power transmission networks in July 2022, MW.

electricity from RES. The implementation of this mechanism is carried out by SE "Guaranteed Buyer", which is obliged to purchase all electric energy from RES generators at a special tariff on the basis of the Law on the Electric Energy Market [3] adopted in 2017. Since March 2022, a number of legislative changes were introduced, which significantly changed the "green"tariff (in particular, the peg to the euro was removed), the conditions and the mechanism of payments were changed as well. As mentioned above, the state's debt to producers under the "green"tariff increased significantly due to the military actions. Therefore, the question arises whether the state will be able to support such a mechanism in the future. Therefore, it is extremely important and urgent to find new mechanisms and ways to develop RES producers.

According to the Ten-Year Plan for Reconstruction of Ukraine [22], published by the National Council for Reconstruction of Ukraine after the consequences of war and presented for the first time at the URC 2022 (Ukraine Recovery Conference) on July 4-5, 2022 in Lugano, Switzerland, the main directions of development of the Ukrainian energy industry are defined as follows:

- Integration with the energy systems of EU countries;
- Decarbonization;
- Optimization of the energy mix and balancing of the energy system;
- Increase of energy efficiency.

In particular, the Plan presents the project of the National Program "Energy Independence and Green Course" [23], which includes points such as the construction of an additional 30 GW of RES and batteries, the construction of smart grids.

As the research shows, 90% of the capacities of producers from alternative sources are connected to distribution networks. Therefore, the development of renewable energy is one of the important points on the way to a decentralized energy system. Also, the government proposes to provide "mini power plants and small generation facilities that will be integrated into the existing power grid" [24]. In particular, the development of distributed generation will provide energy independence and an increase in the security of energy supply to the communities of Ukraine.

Another step towards the development of distributed generation and the development of RES is the introduction of virtual power plants. A virtual power plant is a high-tech system that combines electricity from several producers and consumers at once. Producers in this case can be distributed generation facilities. Consumers are electricity consumers who have refrigeration units, air conditioners, drainage pumps, crushing units, etc. It should be noted that such objects of consumers and producers must be flexible in the production or consumption of electricity. The virtual power plant does not intervene directly in the production process. It regulates facilities that provide support to the power system when the balance between production and consumption is disturbed.

In addition, the concept of creating a cellular energy network (CEN) is being considered for territorial associations [25]. CEN is a set of energy generation and storage centers connected to each other and to consumption centers in a given area.

Considering the experience of the development of RES, i.e., the spread of such facilities throughout the territory of Ukraine, it is reasonable to take into account the available data when studying the above approaches to the development of the national power industry. At the same time, the implementation of these ideas can be one of the methods of support and development of RES producers. Therefore, the approaches of decentralization of the power supply system or creation of a power supply system are promising for solving some consequences of military aggression on the territory of Ukraine and require further research.

5. Conclusions

The analysis of the dynamics of renewable energy development in Ukraine in recent years was carried out, taking into account the specifics of connecting plants to high-voltage or distribution networks. Also, the research shows the distribution of the capacities of RES facilities in the regions of Ukraine.

As a result of Russia's armed aggression, the power industry of Ukraine in general, and more than 1000 MW of RES capacity in particular, need restoration. At the same time, the existing methods of supporting RES producers are insufficient. Renewable energy needs new mechanisms and methods of development of the industry.

One direction for the evolution of the domestic power industry is the development of a decentralized energy system to provide energy independence and security for the citizens of Ukraine. The results of research show that about 90% of generation capacities are connected to distribution networks and only 10% to high-voltage networks. Accordingly, renewable energy is an important part of the distribution network.

Therefore, the issues of supporting alternative generation and the development of distributed generation are interrelated, mutually complementary, relevant, and require further research.

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References

[1] 2022 Rynok VDE. Pidsumky roku ta perspektyvy 2022 [RES market. Results of the year and prospects for 2022] URL https://biz.nv.ua/ukr/markets/vidnovlyuvana-energetika-v-ukrajini-pidsumki-roku-ta-prognozi-2022-vde-50203541.html
[2] Ivanov D 2022 "Detsentralizatsiia" systemy elektropostachannia: pohliad zseredyny ["Decentralization" of the electricity supply system: a view from the inside] URL https://www.epravda.com.ua/columns/2022/12/21/695248
[3] Verkhovna Rada of Ukraine 2017 On Electricity Market URL https://zakon.rada.gov.ua/laws/show/2019-19?lang=en#Text
[4] Geyets V M, Kyrylenko O V, Basok B I and Baseyev Y T 2020 *Science and innovation* **16**(1) 3–14
[5] Geletukha G, Zheliezna T and Prakhovnik A 2015 Analysis of the energy strategies of the EU and world countries and role of renewables in their energy systems UABio Position Paper 13 Bioenergy Association of Ukraine URL https://uabio.org/activity/1114/
[6] Heyets V M 2022 *Visn. Nac. Akad. Nauk Ukr.* (3) 8–17 URL https://doi.org/10.15407/visn2022.03.008
[7] Ostapenko O, Olczak P, Koval V, Hren L, Matuszewska D and Postupna O 2022 *Applied Sciences* **12**(2) 592 ISSN 2076-3417 URL https://doi.org/10.3390/app12020592
[8] Chumachenko O 2022 *Science Notes of KROK University* (3(67)) 39–47 URL https://doi.org/10.31732/2663-2209-2022-67-39-47
[9] Sagaydack J and Kharchenko T 2022 *Bulletin of Sumy National Agrarian University* (1(91)) 33–38 URL https://doi.org/10.32782/bsnau.2022.1.5
[10] Kyzym M O, Shpilevskiy V V, Zinchenko V A and Shpilevskyi O V 2022 *Business Inform* (7(534)) 86–98 URL https://doi.org/10.32983/2222-4459-2022-7-86-98
[11] Yaroshenko Y, Bobrov O and Tsyplenkov D 2022 *Collection of Research Papers of the National Mining University* **69** 193–205
[12] Akinyele D O, Nair N K C, Rayudu R K and Chakrabarti B 2014 Decentralized energy generation for end-use applications: Economic, social and environmental benefits assessment *2014 IEEE Innovative Smart Grid Technologies - Asia (ISGT ASIA)* pp 84–89 URL https://doi.org/10.1109/ISGT-Asia.2014.6873769
[13] Javaid N, Hafeez G, Iqbal S, Alrajeh N, Alabed M S and Guizani M 2018 *IEEE Access* **6** 77077–77096
[14] Nsafon B E K, Owolabi A B, Butu H M, Roh J W, Suh D and Huh J S 2020 *Energy Strategy Reviews* **32** 100570 ISSN 2211-467X URL https://doi.org/10.1016/j.esr.2020.100570
[15] Yevdokymova A, Kolosok S and Petrenko N 2019 *Visnyk of Sumy State University* (4) 108–113 URL https://doi.org/10.21272/1817-9215.2019.4-14
[16] Sokhatska O and Panasyuk V 2022 *Ekonomichnyy analiz* **32**(4) 7–14 ISSN 2219-4649 URL https://doi.org/10.35774/econa2022.04.007
[17] Lobodzinskiy V, Buryk M, Petruchenko O and Illina O 2022 *POWER ENGINEERING: economics, technique, ecology* (1) 57–64 URL https://doi.org/10.20535/1813-5420.1.2022.259182
[18] Kyzym M O, Lelyuk O V and Kostenko D M 2018 *The Problems of Economy* (4(38)) 79–92 URL https://doi.org/10.32983/2222-0712-2018-4-79-92
[19] Lukashevych Y P and Evdokimov V A 2022 *Èlektron. model.* **44**(5) 90–101
[20] Omelchenko V 2022 Ukraine's renewable energy sector before, during and after the war URL https://razumkov.org.ua/en/articles/ukraines-renewable-energy-sector-before-during-and-after-the-war
[21] Guaranteed Buyer 2023 Current information regarding settlements with electricity producers URL https://www.gpee.com.ua/news_item/342
[22] 2022 Ukraine Recovery Plan URL https://recovery.gov.ua/en
[23] 2022 Energy independence and Green Deal URL https://recovery.gov.ua/en/project/program/energy-independence-and-green-deal
[24] Communications Department of the Secretariat of the CMU 2023 Building a decentralized energy system will allow the country to reduce its vulnerability to enemy attacks: Prime Minister URL https://tinyurl.com/2fza2zer
[25] Unigovskyi L 2022 The concept of creating a cellular energy network for the territorial associations in Ukraine URL https://www.linkedin.com/pulse/concept-creating-cellular-energy-network-territorial-unigovskyi/

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Assessment and improvement of digital resilience in the energy crisis caused by missile strikes

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Assessment and improvement of digital resilience in the energy crisis caused by missile strikes

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Abstract. The relentless penetration of information and communication systems into all spheres of life and the widespread use of digital technologies has been called "digital transformation". Different systems demonstrate a different ability to effectively resist risks of any origin and nature, adapt to changes in the environment, maintain rapid recovery and return to maximally stable functioning. Such properties are generally called resilience. If these properties are acquired or enhanced through the use, application and development of digital technologies, we call them digital resilience. To analyze digital resilience, it is suggested to consider digital subscribers, digital needs, digital tools and their dependencies. Practical examples of such dependencies are given, which are formed under the influence of systematic missile attacks of the aggressor on the power energy system of Ukraine. The foundation was laid for a combined digital resilience assessment methodology that includes a metric approach and the theory of topological spaces.

1. Introduction

A society is being transformed to help individuals and communities use knowledge and ideas that help people realize their potential and realize their aspirations [1]. Digital transformation is a characteristic feature of a digital society whose economy is based on information technologies. The semantic field of digital transformation includes such concepts as the digital economy, digital skills, digital rights, e-government, digital innovations and much more. The digital component of existence acquires significant value and becomes an object of attack. The one's ability to resist a direct or indirect impact on the digital component of their being is known as "digital resilience". By the ability to resist, we mean the dynamic property of the individual or a system, which is embedded in its organization (functional scheme) and which serves as the basis for the ability to overcome negative impacts arising from risks, as shown on figure 1 and well-explained in [2]. Digital resilience characterizes how successfully and constructively one overcomes challenges of any origin and nature, adapts to changes in the environment, maintains stable functioning, quickly recovers to the desired balance and evolves after crisis situations based on the use, application and development of digital technologies. Digital resilience can be a property of an individuals, communities, businesses, society, the state as a whole. It is subject to analysis, measurement and improvement. In [3] authors describe the role of digital social support, digital health, and digital identities in the process of adjusting to a new reality for refugees.

Thus, much attention is spent to the resilience of cyber systems. For example, in [4] authors describe resilience metrics which link national policy goals to specific system measures,

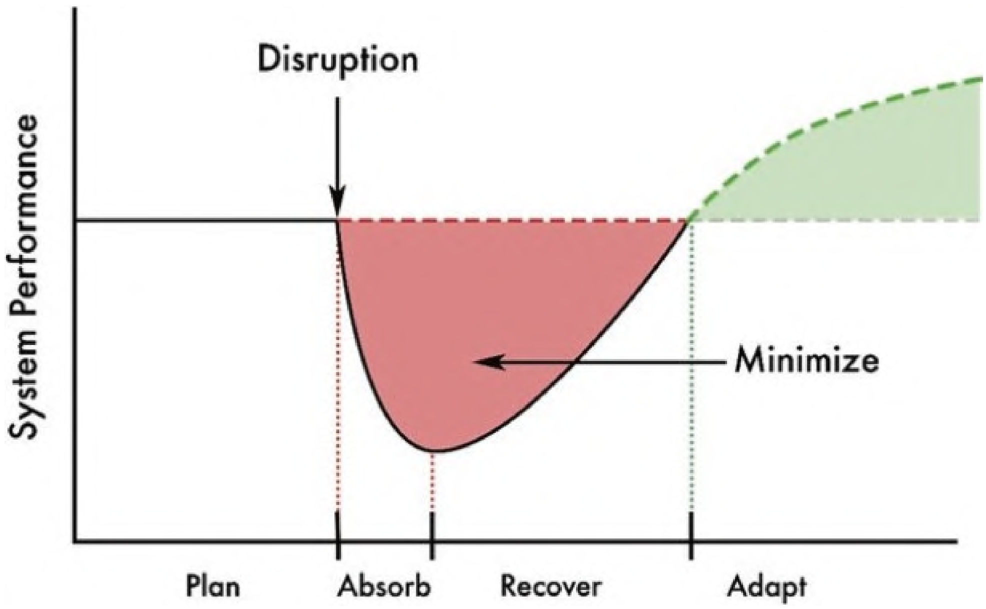

Figure 1. Stages of resilience according to National Academy of Sciences proposal.

such that resource allocation decisions. Being cyber-physical systems, power energy grids have mutual dependencies of their resilience and resilience of both electronic communications and information systems. Clark and Zonouz [5] are noted that resilience of is based on the assumption that a sophisticated intrusion may succeed to evade the deployed protection and runtime detection mechanisms and impact the underlying system services and assets excepting the core functionalities. Based on power systems case study, authors formulate cyber defense policies that ensure the resilience conditions are satisfied.

The experience of Ukraine is extremely valuable for the study of digital resilience. Ukraine is a state that was among the leaders of digital transformation before the large-scale Russian invasion. Unprecedented missile attacks on the main facilities of the power industry lead to massive emergency power outages, which are controlled by the enormous efforts of power network operators. Businesses, telecommunications operators and the general population are trying to adapt to the continuously declining level of electricity supply.

Currently, Ukraine is in transition: instead of scheduled power outages for several hours a day, scheduled inclusions for several hours a day are introduced. In December, 2022 multi-day outages took place. Each business and each household must constantly review their survival options during the growing impact of this negative factor, which directly brings us to the need for resilience analysis. In our opinion, science should contribute to the development of mechanisms for absorption of negative impact, adaptation to the new state and evolution of information and communication systems. This requires the collection, analysis, and systematization of existing experience (especially sectoral) in order to reduce the number of trials and errors in the future when creating resilient information and communication systems in conditions of limitations and uncertainties.

2. Research aim and methodology

To develop methods of increasing the resilience of information and communication systems to threats related to the electric power industry, the following tasks must be solved:

- investigate the most sensitive digital needs of digital subscribers;

- analyze the cyber threats that large-scale power outages pose and how they affect digital needs;
- analyze network architectures, types of electronic communications, data transmission systems, topologies, and determine which combinations can increase the resilience of information and communication systems (ICS) involved in providing the most sensitive information needs of the population and business.

As a result of the analysis, sets of digital subscribers – DS, digital needs – DN, and digital means (or digital tools) – DT will be obtained as depicted on Figure 2. These three sets will form a variety of tuples of three elements each $(ds \in DS, dn \in DN, dt \in DT)$, as well as from two elements based on existing and available combinations:

(i) digital subscriber and one's needs: $(ds \in DS, (dn_1, dn_2, dn_3, ..., dn_n) \in DN)$;

(ii) digital subscriber and available digital means$(ds \in DS, (dt_1, dt_2, dt_3, ..., dt_n) \in DT)$;

(iii) digital needs and acceptable digital means for obtaining them $(dn \in DN, (dt_1, dt_2, dt_3, ..., dt_n) \in DT)$;

(iv) digital means and subscribers that can use them $(dt \in DT, (ds_1, ds_2, ds_3, ..., ds_n) \in DS)$;

and this list is not final.

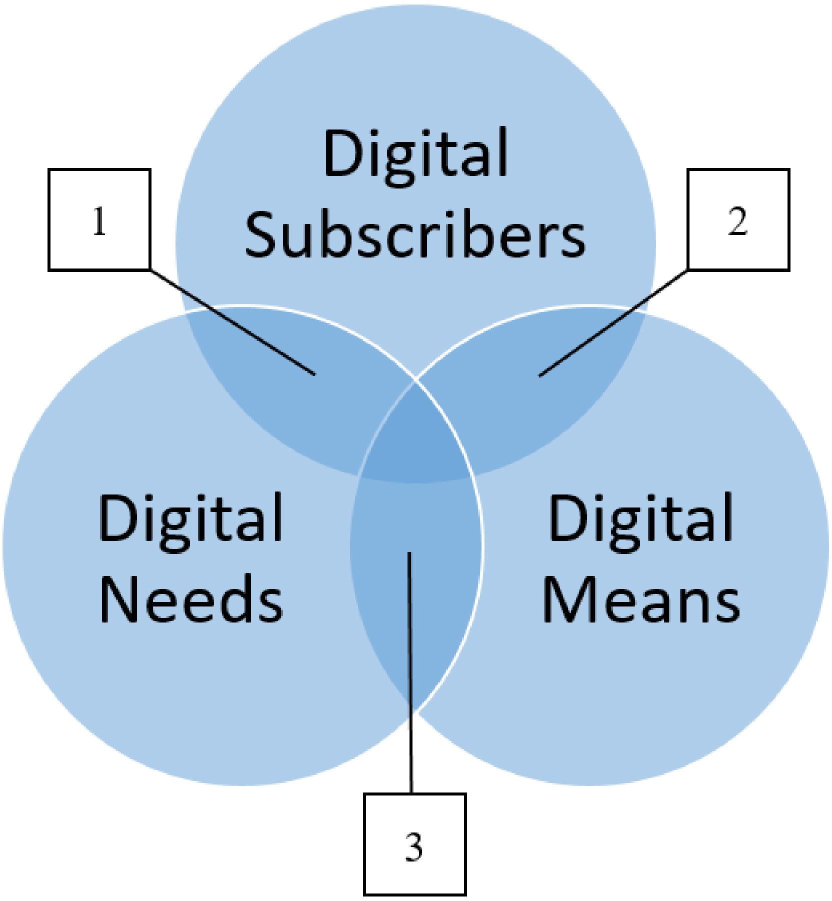

Figure 2. Overlapping sets create tuples: 1 – digital subscriber and one's digital needs; 2 – digital subscriber and available digital means; 3 – digital needs and acceptable digital means for obtaining them.

Let there exist a set $\mathfrak{D}$ such that $\forall ds \in \mathfrak{D}, \forall dn \in \mathfrak{D}, and\ \forall dt \in \mathfrak{D}$. Let there exist a system of elements of this set $\mathfrak{T}$, which includes all possible combinations of these elements, unions and intersections of these sets: $\exists \mathfrak{T} : \emptyset, \mathfrak{D} \in \mathfrak{T}; \forall \mathfrak{D}', \mathfrak{D}'' \in \mathfrak{T} : \mathfrak{D}' \cup \mathfrak{D}'' \in \mathfrak{T}; \mathfrak{D}' \cap \mathfrak{D}'' \in \mathfrak{T}$.

Then $\mathfrak{T}$ corresponds to the definition of topology on the set $\mathfrak{D}$, and a couple $(\mathfrak{T}, \mathfrak{D})$ corresponds to the definition of topological space. Individual elements of the topology represent network structures [6], that can be researched using graph theory, complex network theory, and topological space theory to develop models and methods for enhancing digital resilience.

Let's look inside of those structures. For the operation of an ordinary business, for example, a chain of retail stores, the local ICS of each store, the ICS of the head office, usually the ICS of the operator of the datacenter where ERP system resides, and several more ICSs belonging to the operators of electronic communications may be involved (modern data transmission systems are mostly convergent [7], and therefore have their own information communication systems). The functioning of the mass media (including broadcasting systems), state information services for the society, transport, healthcare, education are connected with ICS. It is also important to realize the main role of ICS in personal communication and the possibility of being in touch. First of all it's about global software platforms of instant messengers and social networks. These examples testify to the existence of an open set of cyber-social systems, the functioning of which is a component of the resilience of the entire society.

In the vast majority of cyber-social systems, the user gets access to digital services via the Internet. Therefore, sufficient connectivity and bandwidth of the global network is the most important factor in the stability of ICS, and therefore in digital resilience. Thus, the availability of Internet access is the most important factor of information security, which affects the availability of information.

3. Examining examples of dependencies between power grid and digital resilience

The Ukrainian power energy industry is unique in Europe due to the presence of a large transport system with nodes whose capacity reaches 3 GVA, as well as unique 750 KV transformers which are custom design equipment. However, these main nodes are the easiest prey to the enemy due to missile terror (figure 3).

Massive Russian terrorist missile attacks on Ukraine's electricity industry lead to massive blackouts that are difficult for power grid operators to control. One of the major missile attacks led to a blackout of the country's entire power grid for 12 hours [9]. Degradation of electricity supply goes through several stages. At the end of November 2022, instead of planned power outages (for several hours per day), planned power-ups for several hours per day were introduced, as shown on figure 4. By weekdays in rows, we can see darkest cells representing planned outages, gray ones show possible outages in case of overloads in the energy system, and pairs of bright cells mark hours of guaranteed provision of power. In fact, the schedule is rarely followed.

Russia widely uses a variety of munitions: from cheap Iranian barrage munitions (Shahed 136 drones) to complex hypersonic missiles of great destructive power. Despite the huge successes of the air defense of Ukraine, during each massive enemy strike, several munitions reach the target, causing new destruction to the energy system [10]. In the future, new missile attacks and regular multi-day outages are expected. This is a real test for the modern digital society based on information technologies and electronic communications.

Figure 5 shows a generalized individual-centric digital chain that connects a digital actor with a set of digital needs using a set of digital means. As we can see, the key element of digital resilience is the means of electronic communications (dt set). The initial element of digital resilience is the digital subscriber (dt set) – consumer of digital services. This is either an individual or a legal entity, the needs of which vary, and the availability of tools for them is also slightly different.

The risks associated with the lack of electricity power affect all elements without exception,

Figure 3. Power autotransformer destroyed by missile strike in Rivne region [8].

but not to the same extent. Let's consider what lessons Ukraine learned during the last few months of 2022.

3.1. Problems on the subscriber's side

The main component that an individual needs to meet digital needs is the electrical power supply of one's office or home or other place where private information communication systems reside. The majority of Ukrainians live in apartment buildings, they have no redundant power supplement systems or local generation facilities. To cover multi-hour power outages, private individuals and small offices massively purchase or construct *uninterruptible power supplies* (UPS). Typical UPS models for home or small office not designed for long-term autonomous operation. Their batteries designed to provide electric current for a maximum of tens of minutes. The use of non-standard batteries of large capacity leads to overheating the UPS both during long-term autonomous operation and during charging of such enormous batteries. Ignoring this danger could result in battery explosion and fire.

The use of systems based on *car batteries* has also gained popularity. Car starter batteries proved to be ineffective as a source of long-term supply of electric current. This is related to the chemical properties of acid batteries. They are prone to sulfation during deep discharge, so they can relatively reliably deliver only 0.3 part of their nominal capacity. In addition, their presence and use indoors causes additional safety problems due to the evaporation of harmful substances from the battery [11].

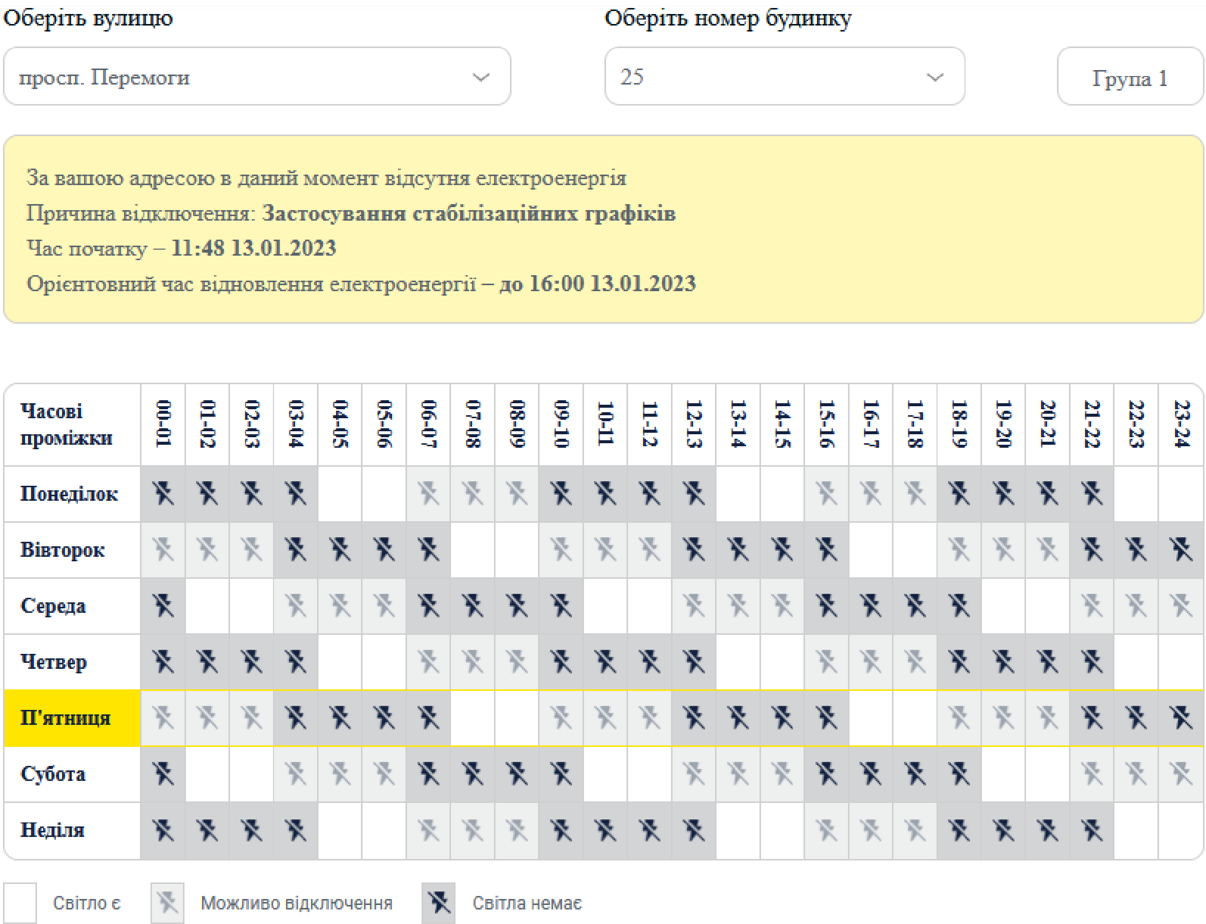

Figure 4. The real-life schedule of planned and emergency power outages for average district of the Kyiv city introduced by power distribution company DTEK (`https://dtek-kem.com.ua`).

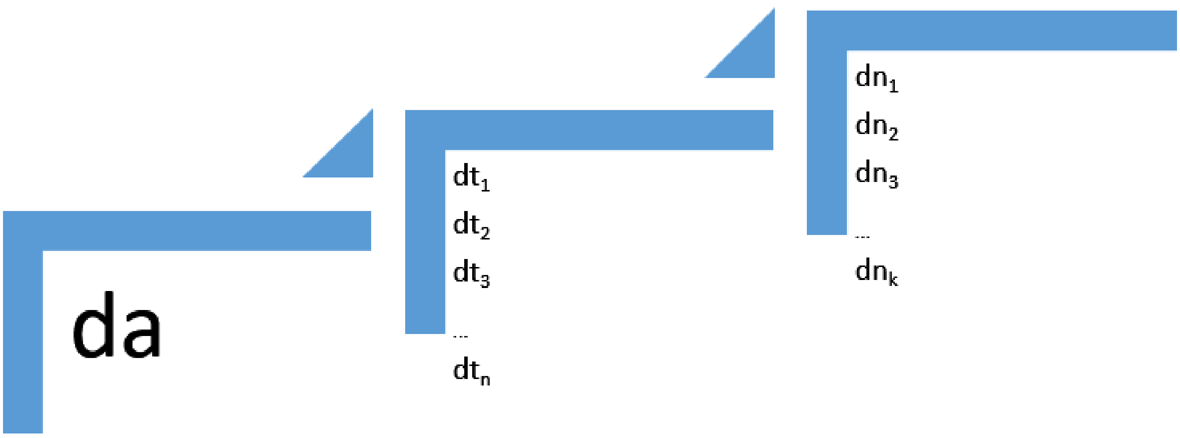

Figure 5. Generalized "digital chain" from digital actor to digital needs.

The use of *specialized low-power UPS* for individual devices, primarily for home wireless routers, has become popular. This makes sense if the local Internet provider has ensured the operation of its network during continuous power outages. The issue of Internet providers will be discussed below. In terms of human safety, this is a very attractive solution. But it turned out that in the mode of long-term power outages, accelerated degradation of batteries of all main types occurs.

Attempts to use alternative generation (primarily *solar generation*) cause many purely technological difficulties. Residents of individual apartments who are able to place solar panels on the outside and face south can count on partial success. But Russians began their missile terror against critical civil infrastructure in mid-autumn, when the duration of daylight shortens and cloudy days increase. Therefore, the effectiveness of the panels until spring will be very low, even for the lucky ones. Solar panels should be centrally located on the roofs of high-rise buildings. It is clear that such a solution requires large project works at the level of the entire building, not a separate apartment.

The use of *generators based on gasoline or diesel engines* requires major decisions at the level of entire buildings. There are strict sanitary and fire regulations for the installation and operation of such generators. In addition, there is a significant problem of legal storage of fuel stocks, since in Ukraine this type of activity requires obtaining a license.

The use of *mobile Internet* by end users is the most popular. There are two main factors. First is that mobile Internet access in Ukraine is cheap comparing to Europe. Besides, after declaration of martial law mobile operators opened a free roaming between their networks. Second factor is that end mobile devices (4G modems, smartphones, tablets, laptops, POS terminals) have their own batteries, which can be additionally recharged from pocket power banks. However the operators' networks are affected by problems which will be described below.

3.2. Problems of the access to digital needs

Problems of the access to digital needs are mostly related to problems of architecture and topology of local Internet access provider networks. Let's review a few most common ones.

Ethernet – the main technology for Internet access in high-rise buildings. UTP cable and fiber optics are used. A typical network is divided into 2 or 3 layers – core, distribution and access. While the core layer equipment is always located in places with redundant power supplement, the equipment of other layers is closer to subscribers and much more suffers power outages. These are Ethernet switches serving the connection for several apartments (typically from 16 to 48). An attempt to provide them with large-capacity batteries ran into problems of rapid degradation of batteries due to long power outages and insufficient charge as a result. The use of the most modern type of LiFePo4 batteries with charge controllers of the appropriate power has not yet been widely introduced due to the high cost of these devices and insufficient saturation of market [12].

DOCSIS – another "last mile access" technology widely used in Ukrainian cities. DOCSIS is based on the use of coaxial cable (HFC), which used to branch out the terrestrial television signal. The architecture is shown in figure 6 and provides for the presence of a cable management telecommunication system (CMTS) per group of subscribers, as well as repeaters (amplifiers). All these devices require power supply. According to the reviews of users of the operator Volia Cable in Kyiv, this operator does not have any particular advantages in network stability in time of continuous power outages.

ADSL is a technology based on the use of a physical landline telephone network (plain old telephone service). This is a legacy technology for Ukraine, which, however, is still widespread in the developed countries of Europe [13]. Its attractiveness is that the network uses rather long last miles (up to several kilometers) without repeaters, and the operator's equipment is located next to the PSTN (telephone stations), which is always a priority consumer in the power grid and is provided with backup power as critical infrastructure. The main disadvantage of ADSL is the limited speed (usually up to 3 Mbps upstream, and 8 to 20 Mbps downstream). Many Ukrainian Internet users would prefer to return to this technology due to the inability of other

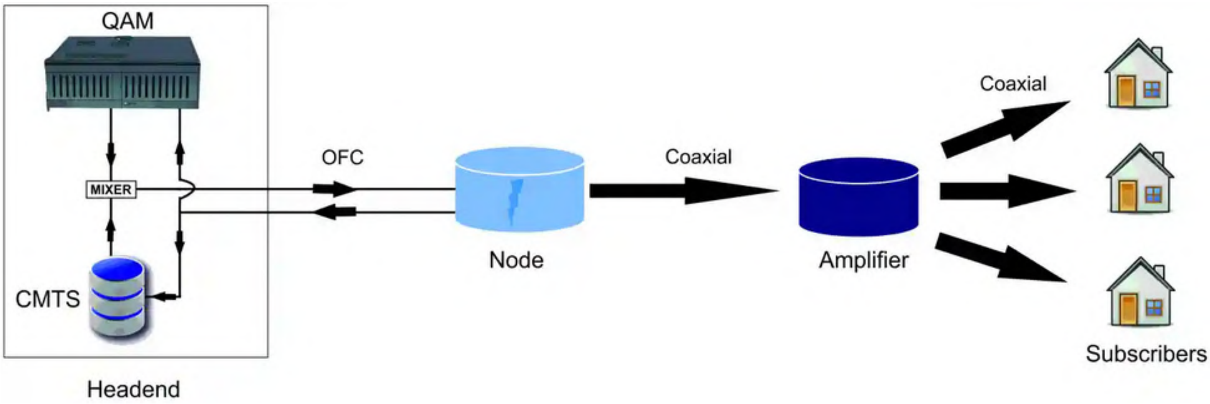

Figure 6. DOCSIS topology requires CMTS at provider's site and amplifiers at customers' buildings to be supported by uninterruptible power supplies.

providers to support networks. But it turned out that in the course of the gradual degradation of landline telephone communication, the infrastructure of copper cables is often broken and destroyed.

Passive optical networks, known as PON, is a widely known and efficient optical network architecture. Its main advantage is coverage of the widest range of subscribers using the minimum number of ports on the operator's side. This achieved by using totally passive devices called optical splitters for creating mixed tree topology, as shown on figure 7. So only optical line units (OLT) at provider's side and optical network terminals (ONT) at subscriber's side require power supply.

The problem with PON is that it is a relatively new technology. It is widely used to build new broadband Internet access networks, while the main urban networks are result of merges and acquisitions of small networks of past and keep growing on old technologies. At the moment, old networks are already physically interfering with the laying of new communications. The process of abandoning Ethernet and DOCSIS will obviously continue for many years.

Mobile (cellular) networks also suffer from power outages. 3G and 4G technologies require a high density of base stations from operators. Their location mostly does not provide for the possibility of using backup generators, and their power excludes the possibility of long-term operation from batteries. In the city of Kyiv, operator networks can be overloaded during power outages, especially in uptowns and suburbs, where the density of base stations is lower. According to the adopted decisions, the mobile operators consider the provision of voice communication as a priority service. Other services may degrade to the level of 20 percent of the nominal [15].

A review of access technologies would be incomplete without *satellite systems*. The use of a fixed or mobile satellite Internet system is also gaining popularity. Several satellite operators do their business in Ukraine. But above all, the leader is Starlink. The supply of Starlink terminals takes place under several international programs at the expense of the state budget of Ukraine, international partners and sponsors. In addition, a significant number of Starlink terminals were purchased by private consumers [16]. The advantages of such a solution are independence from local networks and operators, relative connection reliability and bandwidth which fully meets the needs of a private user or, with some restrictions, a group of consumers. The disadvantages are that in cities with high-rise buildings, users have a problem with the location of antennas (figure 8) and their power supply at the level of a particular residence. Solving problems requires centralized solutions, but Starlink terminals have proprietary limitations that require significant costs to obtain the possibility of collective use of the station for the benefit of several consumers

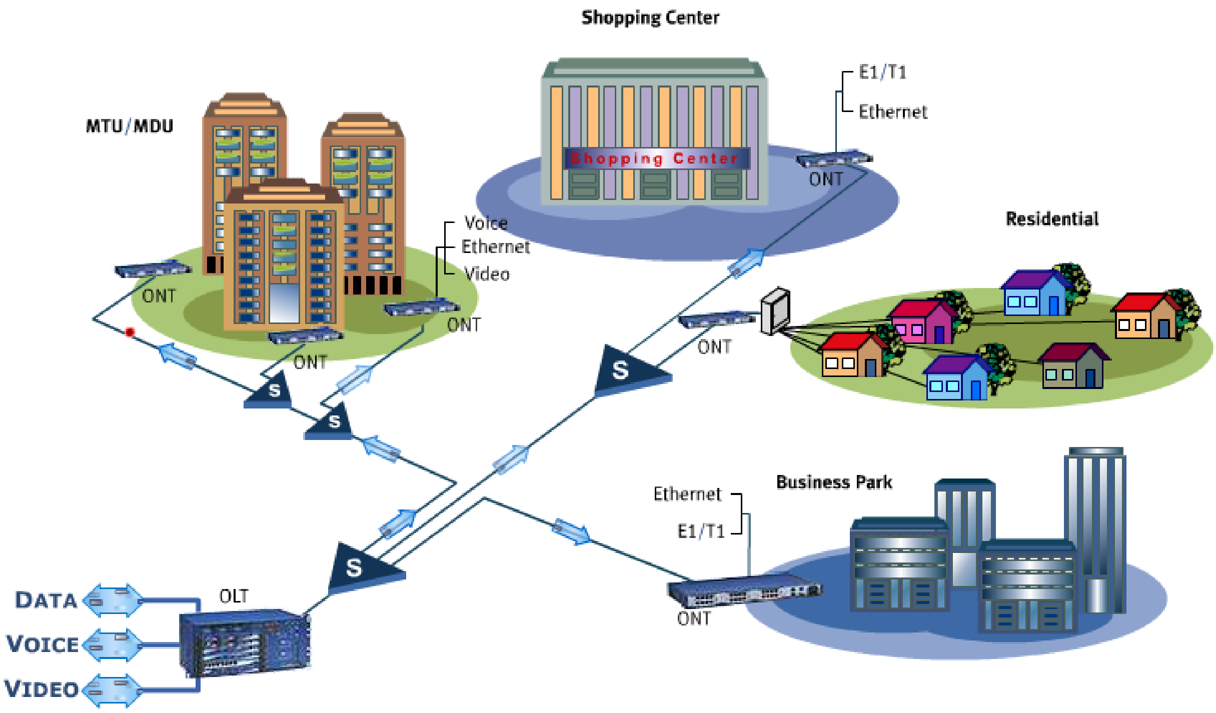

Figure 7. In Passive Optical Network topology passive optical splitters (S) are widely used. Optical line units (OLT) at provider's side and optical network terminals (ONT) at subscriber's side require power supply [14],

Figure 8. Examples of antenna installation of Starlink stations in cities of Ukraine (photo by `https://highload.today`).

(several apartments or offices).

Also worth noting that Ukraine has widely announced the deployment of so-called "*Invincibility points*", designed to provide heating, hot drinks, electricity for charging private devices and, in some places, Internet access. The following structural elements are necessary for the successful functioning of "Invincibility point":

- professional electric generator capable of working continuously for a long time (which is not provided by widespread household gasoline generators). Its output power capacity must correspond to the expected electricity consumption;
- structured cable system for the possibility of safely connecting several dozen devices with lithium batteries. For instance, the charge of a modern laptop consumes up to 65W, connecting 50-100 laptops requires a serious attitude to the cable system and load calculation;
- reliable Internet access, taking into account the features of operator technologies, which were observed above;
- professional equipment for building a Wi-Fi network capable of serving dozens and hundreds of devices at the same time (home Wi-Fi routers and access points are not suitable for this).

The practical experience of the city of Kyiv is that the premises of catering establishments, schools, etc. receive the status of "Invincibility points". Figure 9 demonstrates this. Each institution independently solves the problems of heating, energy, sanitary requirements, access to the Internet. "Invincibility points" are effective from the point of view of digital resilience, but their impact cannot be called significant.

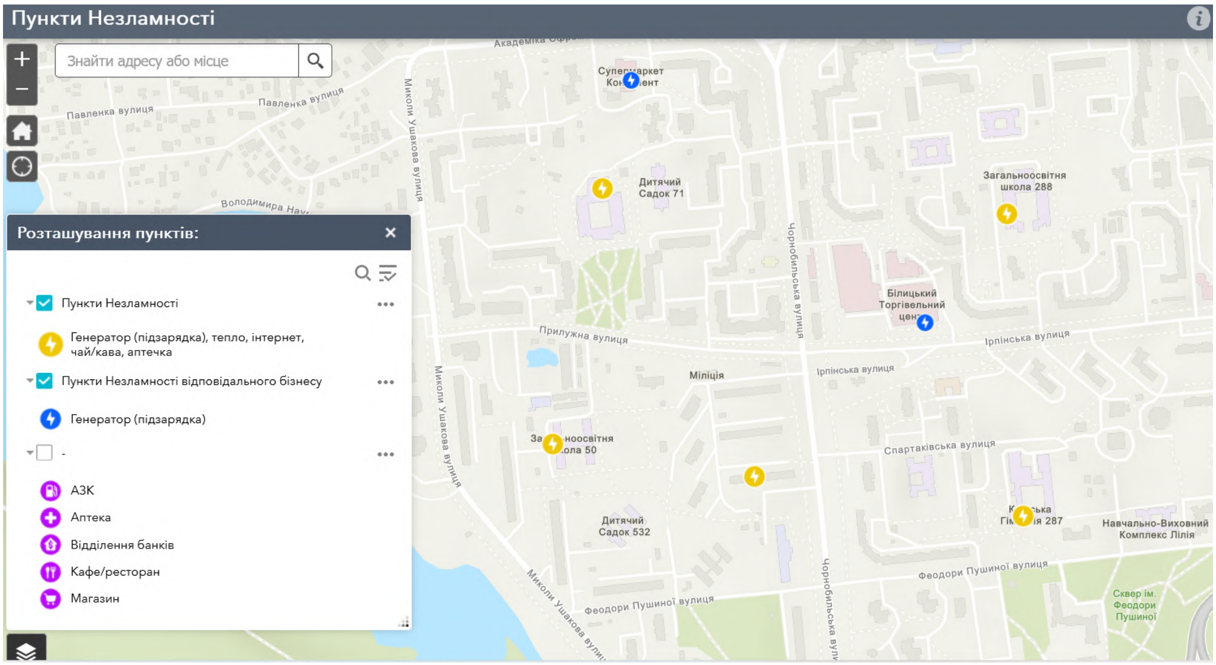

Figure 9. Map of Invincibility points in random Kyiv uptown district with population 45..60 thousand residents. Blue signs point to local stores and tell there is only charging available. Yellow signs mean that Internet access and hot drinks also available, and they point to school buildings and one social services office [17].

3.3. Generalization of the given examples

According to the proposed classification, the chain from a digital subscriber to a digital need at the very initial stage contains a large number of options for ensuring the digital resilience of the subscriber itself and their means. Each digital tool can be analyzed and compared with others that provide a similar result. This can be, for example, a SWOT analysis. But to generalize the result, the most promising is the development of metrics that characterize the most effective resilience tools, based on their availability, cost, time of implementation, reliability and other properties. Such metric approach approved by many researchers, e.g. Linkov et al [4] and Clark and Zonouz [5]. Whereas this approach was applied for evaluation of most secure paths combination in [18], it was combined with risk management theory applied to global network topology. Such risk-aware metrics can be also introduced to evaluation of digital resilience. For this purpose, we offer to review each property of a digital tool as a component of risk, either a factor of cost or factor of likelihood. For example, let's define some of properties for digital tools as discrete:

- cost c_{dt} – how much does it cost to get this digital tool and use it;
- accessibility a_{dt} – implementation agility, or how easy it is to access this tool (or switch to this tool);
- reliability r_{dt} – a measure of the ability to perform the required functions in the given modes and conditions of this tool's use;
- power autonomy p_{dt} – how much independent this tool is from power outages in comparison to other functionally equivalent digital tools.

Then it's possible to evaluate digital resilience $\mathfrak{R}$ for an average household digital tools, which include redundant power supplies (dt_1), diversified Internet access providers (dt_2), personal awareness how to alternate power source for Internet access equipment (dt_2) and so on:

$$\mathfrak{R} = f(dt_1, dt_2, dt_3, ...dt_n),$$

where dt_n is tied to $(c_{dt}, a_{dt}, r_{dt}, p_{dt})$ in a some way which should be analysed and formalized on future steps of this study.

Similar considerations can be made when analyzing network providers, and data centers, and each element of the entire chain between the consumer and the service. This leads us to generalisation of metric evaluation of digital resilience.

4. Conclusions

Representation of individual components of the digital world in the form of a topological space opens the way to the study of the problem of digital resilience through the study of group properties, characteristics, dynamics of a large number of network structures.

In the future, the study provides an analysis of means and measures to ensure the resilience of digital service providers (from online stores to large data centers) during the crisis of the electric power industry. In addition, it is necessary to develop metrics that characterize the effectiveness of resilience tools, based on their availability, cost, implementation agility, reliability and other criteria.

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References

[1] Kyushu-Okinawa Summit 2000 (Official Documents) 2000 Okinawa Charter on Global Information Societ URL https://www.mofa.go.jp/policy/economy/summit/2000/documents/charter.html
[2] Linkov I and Trump B D 2019 *The Science and Practice of Resilience* Risk, Systems and Decisions (Cham: Springer) ISBN 978-3-030-04565-4 URL https://doi.org/10.1007/978-3-030-04565-4
[3] Udwan G, Leurs K and Alencar A 2020 *Social Media + Society* **6**(2) 2056305120915587 URL https://doi.org/10.1177/2056305120915587
[4] Linkov I, Eisenberg D A, Plourde K, Seager T P, Allen J and Kott A 2013 *Environment Systems and Decisions* **33**(4) 471–476 ISSN 2194-5411 URL https://doi.org/10.1007/s10669-013-9485-y
[5] Clark A and Zonouz S 2019 *IEEE Transactions on Smart Grid* **10**(2) 1671–1684 URL https://doi.org/10.1109/TSG.2017.2776279
[6] Zubok V and Mokhor V 2022 *Cybersecurity of the INTERNET Topology* (Ukraine: G.E.Pukhov Institute) ISBN 978-966-02-9929-0 URL https://zenodo.org/record/6795229
[7] Radicella S and Grilli D (eds) 2002 *Evolution and Convergence in telecommunications* (*ICTP Lecture Notes* vol 11) (Trieste: The Abdus Salam ICTP Publications & Printing Services) ISBN 92-95003-16-0 URL https://www.osti.gov/etdeweb/servlets/purl/20909656
[8] Horbachova A 2022 Na Rivnenshchyni okupanty vdaryly po obiektakh enerhosystemy: de vidkliuchat svitlo URL https://www.unian.ua/economics/energetics/raketniy-udar-po-rivnomu-vid-raket-okupantiv-postrazhdali-ob-yekti-energosistemi-12020256.html
[9] Semenova T 2022 Ukraine war latest: Millions still without electricity after Russia's Nov. 23 mass strikes URL https://kyivindependent.com/national/ukraine-war-latest-millions-still-without-electricity-after-russias-nov-23-mass-strikes
[10] Zelenskyy V 2022 Russia still has enough missiles for several massive strikes, we have enough determination and self-belief to return ours – address of the President of Ukraine URL https://www.president.gov.ua/en/news/rosiyi-she-vistachit-raket-dlya-kilkoh-masovanih-udariv-nam-79917
[11] West Virginia University 2007 Lead-Acid Battery Safety URL https://www.ehs.wvu.edu/files/d/0c032a15-ce2c-49b8-8d44-2d6391af0335/lead-acid-battery-safety.pdf
[12] Metaye R 2023 LiFePO4 battery (Expert guide on lithium iron phosphate) URL https://climatebiz.com/lifepo4-battery/
[13] European Commission and Directorate General for Communications Networks, Content and Technology 2022 Broadband Coverage in Europe 2021: mapping progress towards the coverage objectives of the Digital Decade Final report European Commission DG Communications Networks, Content & Technology Luxembourg URL https://doi.org/10.2759/642537
[14] 2019 PON Passive Optical Network URL https://www.reachoptics.com/pon-passive-optical-network-n106.html
[15] Prysiazhna L 2022 U vypadku povnoi dovhostrokovoi vidsutnosti elektroenerhii "Kyivstar" zmozhe pidtrymuvaty lyshe do 20% merezhi u velykykh mistakh [In the event of a complete long-term power outage, "Kyivstar" will be able to support only up to 20 percent of the network in large cities] URL https://tinyurl.com/biz-liga-kyivstar
[16] Sheetz M 2022 About 150,000 people in Ukraine are using SpaceX's Starlink internet service daily, government official says URL https://www.cnbc.com/2022/05/02/ukraine-official-150000-using-spacexs-starlink-daily.html
[17] 2022 Punkty Nezlamnosti URL https://nezlamnist.gov.ua/#map
[18] Zubok V and Kotsiuba I 2020 Empirical Study of New Metrics for the Internet Route Hijack Risk Assessment *Selected Papers of the XX International Scientific and Practical Conference "Information Technologies and Security" (ITS 2020), Kyiv, Ukraine, December 10, 2020* (*CEUR Workshop Proceedings* vol 2859) ed Dodonov A G, Lande D V, Stoianov N T, Tsyganok V V, Snarskii A A, Chertov O and Bozóki S (CEUR-WS.org) pp 199–209 URL https://ceur-ws.org/Vol-2859/paper17.pdf

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Research and calculation of the levels of higher harmonics of rotary electric machines in active-adaptive networks

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Research and calculation of the levels of higher harmonics of rotary electric machines in active-adaptive networks

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Abstract. In the materials of the article, the parameters of the higher harmonics of the groove frequency are analyzed, which affect the reliability of the operation of electrical equipment and the loss of electrical energy in active-adaptive networks. The influence of higher harmonics of rotary electric machines on the modes of operation of active-adaptive networks and their power equipment is considered. It was established that this influence depends on the energy level of higher harmonics and the modes of operation of active-adaptive networks. A technique is proposed that allows determining the levels of groove harmonic components in the phase windings of electric machines. The calculation of the energy level of higher harmonics was carried out taking into account the electromagnetic asymmetry of rotating electric machines and asymmetric modes of operation of three-phase electric networks using the method of phase coordinates. The obtained results are based on theoretical and experimental studies of the influence of higher harmonics of rotating electric machines on the modes of operation of electrical networks and power energy equipment.

1. Introduction

The quality of electrical energy significantly affects the reliability and efficiency of electrical networks and power equipment. One of the important indicators of the quality of electrical energy is the level of higher harmonics, which causes non-sinusoidal modes of operation of electrical networks [1, 2].

The nature of higher harmonics is diverse. The influence of higher harmonics of rotating electric machines (synchronous generator, asynchronous motor, etc.) on the operating modes of the electric network has not been sufficiently investigated. The relevance of this issue is increasing with the development of active-adaptive networks and the introduction of wind power plants [3, 4].

The theoretical and practical relevance of the problem of higher harmonics in electrical networks is confirmed by a number of publications, both by foreign [5, 6] and domestic specialists [7, 8].

Significant losses in power supply systems associated with low quality electrical energy require additional research into the nature of higher harmonics at industrial enterprises [9, 10]. The results of research into the nature of higher harmonics in power inverters and means of combating them are effectively implemented [11, 12]. Extensive theoretical and practical experience in the quality of energy resources is reflected in normative documents taking into account the European education for the electric power industry of our country.

Modern trends in the development of electrical networks, namely, the introduction of active-adaptive networks, introduce new aspects regarding the quality of electrical energy [13, 14]. This requires constant control of power quality parameters, and in particular the levels of higher harmonics, in real time [15, 16]. The study of the nature of individual harmonics is of significant practical importance. This is confirmed by the study of, for example, third (saturation of the magnetic circuit) and toothed harmonics, which appear as a result of the unevenness of the air gap of rotating electric machines [17, 18]. Therefore, the study of groove harmonics is relevant.

The purpose of the study is to obtain scientific results regarding the nature of groove harmonics of rotating electric machines and to establish the characteristics of their distribution in distribution electrical networks. To achieve the purpose, the following objectives were set:

- to develop a methodology for calculating currents and electromotive force of the groove frequency of rotary electric machines for active-adaptive networks;
- determine the dependences of the levels of groove harmonics of the electrical network.

2. Results

Higher harmonics of distribution electrical networks have a constructive or technological nature. Each harmonic component has one or more sources and a defined propagation space. The amplitude value of the higher harmonic and its flow paths are determined by the interaction of the inductive and capacitive elements of the electrical network. The most unpleasant case is the case of resonance of higher current or voltage harmonics in electrical networks and large enterprises. The manifestation in time determines the random or systematic nature of higher harmonics [19, 20].

In the process of operation, electric rotary machines generate groove harmonics in the electrical network [21, 22]. The appearance of these harmonics is related to the magnetomotive force of the rotor winding. Their frequency can be determined by the expression:

$$\omega_n = \omega_1 \cdot \left[\frac{z_n}{p} \cdot (1 - S) \pm 1\right], \tag{1}$$

where ω_1 is the cyclic frequency; z_n is the number of grooves on the rotor; p is the number of pairs of poles; S is the slip.

The amplitude value of these harmonics is determined by the design parameters of the electric machine and the network voltage. The significant danger of groove harmonics is caused by the dependence of these frequencies on the network frequency and slippage, which can lead to resonance phenomena [23, 24].

Determining the levels of higher harmonics by experimental removal of curves taking into account electromagnetic asymmetry on real electric machines is associated with a large amount of labor, due to the need to manufacture special calibration stands [25, 26].

Finding by calculation the values of higher harmonics corresponding to the maximum permissible asymmetry of the electric machine allows to avoid working with bulky calibration stands. In this case, only verification tests of several electric motors are required [27, 28].

The method of calculating the energy level of higher harmonics in the form of the sum of the squares of the electromotive force of the groove harmonics, taken when each of the three phases of the stator winding is turned off in sequence, is based on the determination of the dependence of magnetic losses from the groove harmonics of the magnetic field in the air gap on the degree of electromagnetic asymmetry [29, 30].

The energy level of the slot frequency induction harmonics characterizes the magnetic losses in steel from the slot order magnetic field. Specific magnetic losses in steel are determined by the expression:

$$P_{mg} = \varepsilon_g \cdot \frac{f}{50} \cdot B^2 + \sigma \cdot \left(\frac{f}{50}^2\right) \cdot B^2, \tag{2}$$

where P_{mg} is the specific magnetic losses in steel; ε_g is the specific losses from hysteresis at $f = 50$ Hz and $V = 1$ T; σ is the specific losses from eddy currents at $f = 50$ Hz and $V = 1$ T; B is the magnetic induction; f is the frequency of magnetic induction.

The specific magnetic losses in steel from the groove harmonics of induction are determined by the expression:

$$P_{mg} = \varepsilon_g \cdot \frac{f}{50} \cdot \frac{1}{2\pi \cdot T_z} \cdot \int_0^{2\pi}\int_0^{T_z} B_n^2(\varphi, t) d\varphi \cdot dt + \sigma \cdot \left(\frac{f_n}{50}\right)^2 \cdot \frac{1}{2\pi \cdot T_n} \cdot \int_0^{2\pi}\int_0^{T_n} B_n^2(\varphi, t) d\varphi \cdot dt, \tag{3}$$

where $f_n = \frac{\omega_n}{2\pi}$ is the electrical frequency of the groove harmonic of induction; $T_z = \frac{2\pi}{\omega_z}$ is the the period of the groove harmonic of the induction; $K_n = \varepsilon_g \cdot \frac{f_z}{50} + \sigma \cdot (\frac{f_n}{50})^2$ is the power loss factor; $B_n(\varphi, t)$ is the spatio-temporal distribution of magnetic field induction in a gap with electromagnetic asymmetry; ω_n is the angular frequency of the groove harmonic of induction (upper and lower).

Will find the specific magnetic losses from the upper slot harmonic of the induction with frequency $\omega_{up} = \omega_1 \cdot [\frac{z_n}{p} \cdot (1 - S) + 1]$ in the three-phase mode of operation, substituting the expression for the spatio-temporal distribution of the slot frequency induction for the three-phase mode:

$$P_{mgup} = K_n \cdot \frac{1}{2\pi \cdot T_n} \cdot \int_0^{2\pi}\int_0^{T_n} B_{up}^2(\varphi, t) d\varphi \cdot dt, \tag{4}$$

Integrating within the range from 0 to 2π and taking into account that for an even whole number, all components containing factors of the form $\sin k \cdot \pi \cdot (Z_1 \pm n)$, where k and n are the integers, obtain the final expression for specific magnetic losses from the upper slot frequency of induction, taking into account the spatial distribution of conductivity air gap with asymmetry and the obtained expressions for the coefficients of the series $\lambda_{\alpha 0}$ and λ_n :

$$P_{mgup} = \frac{1}{16} \cdot K_n \cdot (\lambda_0 \cdot \lambda_{j1} \cdot F_1)^2 \cdot \left(\frac{1}{2} \cdot \lambda_{\alpha 0}^2 + \frac{1}{4} \cdot \lambda_{\alpha 0}^2 + \lambda_{n1}^2 + \frac{1}{2} \cdot \lambda_{i1}^2 \cdot \lambda_{n1}^2\right), \tag{5}$$

In this expression $\frac{1}{2} \cdot \lambda_{\alpha 0}^2 + \lambda_{n1}^2 = K_{\alpha 1}$ there is a coefficient of losses due to magnetic asymmetry, taking into account only the first term of the series λ_n . According to mathematical transformations:

$$K_{\alpha 1} = \frac{8 - 2 \cdot a_m^2 - 8 \cdot \sqrt{1 - a_m^2}}{a_m^2 \cdot (1 - a_m^2)}, \tag{6}$$

where a_m is the coefficient of relative electromagnetic asymmetry.

Carrying out similar transformations taking into account the first two and three terms of the series, it is possible to obtain the corresponding coefficients $K_{\alpha 2}$ and $K_{\alpha 3}$, which refine the calculation:

$$K_{\alpha 2} = \frac{1}{2} \cdot \lambda_{\alpha 0}^2 + \lambda_{n1}^2 + \lambda_{n2}^2; \tag{7}$$

$$K_{\alpha 3} = \frac{1}{2} \cdot \lambda_{\alpha 0}^2 + \lambda_{n1}^2 + \lambda_{n2}^2 + \lambda_{n3}^2. \tag{8}$$

In the general case, taking into account all terms of the Fourier series, the expression for the specific magnetic losses from the upper slot frequency of induction will have the form:

$$P_{mgup} = \frac{1}{16} \cdot K_{\alpha n} \cdot (\lambda_0 \cdot \lambda_{j1} \cdot F_1)^2 \cdot \left(1 + \frac{1}{2} \cdot \lambda_{i1}^2\right) \cdot K_{\alpha n}, \tag{9}$$

where $K_{\alpha n}$ is the electromagnetic asymmetry coefficient taking into account the terms of the Fourier series λ_n.

$$K_{\alpha n} = \frac{1}{2} \cdot \lambda_{\alpha 0}^2 + \sum_{n=1}^{\infty} \lambda_n^2 = \frac{4}{1-a_m^2} \cdot \left[\frac{1}{2} + \sum_{n=1}^{\infty} \left(\frac{1-\sqrt{1-a_m^2}}{a_m}\right)^{2n}\right]. \tag{10}$$

Since at any values $0 < a_m < 1$ the values of the function $q = \left(\frac{1-\sqrt{1-a_m^2}}{a_m}\right)^2$ are also in the range from 0 to 1 (figure 1), the sum will have a finite value and the expression for $K_{\alpha n}$ in its final form will have the form:

$$K_{\alpha n} = \frac{4}{1-a_m^2} \cdot \left[\frac{1}{2} + \frac{1-\sqrt{1-a_m^2}}{a_m^2 - (1-\sqrt{1-a_m^2})^2}\right]. \tag{11}$$

Thus, the specific magnetic losses from the upper slot harmonic of the induction depend on the value of the relative electromagnetic asymmetry. The nature of this dependence is completely determined by the nature of the graph.

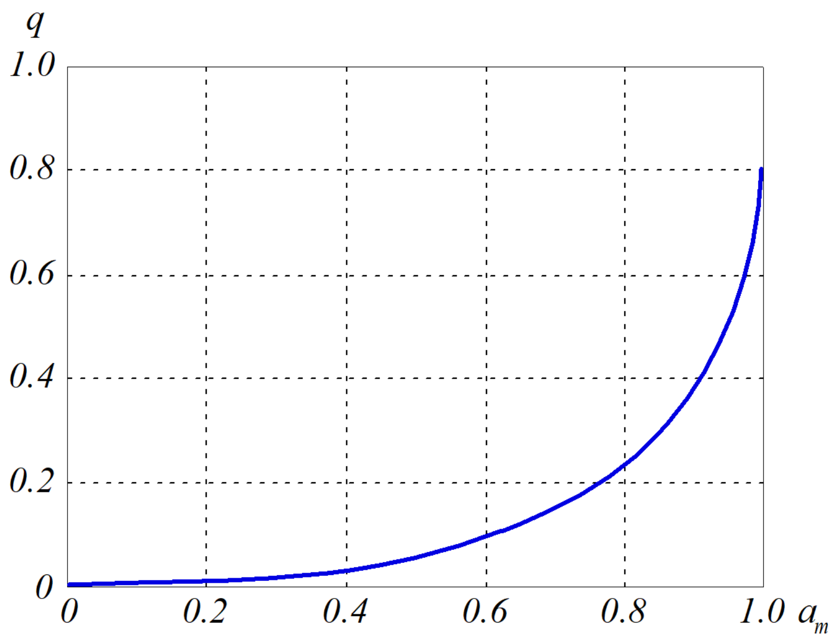

Figure 1. Range of function values $q = \left(\frac{1-\sqrt{1-a_m^2}}{a_m}\right)^2$.

When determining the losses by the coefficient $K_{\alpha n}$, taking into account only the first two members of the harmonic series λ_n the relative error of the calculation γ_n with an electromagnetic asymmetry of up to 50% does not exceed 2%, and then it begins to grow monotonically, and in the region of large asymmetry ($a_m = 80 + 90\%$) is 10 + 25% (figure 2).

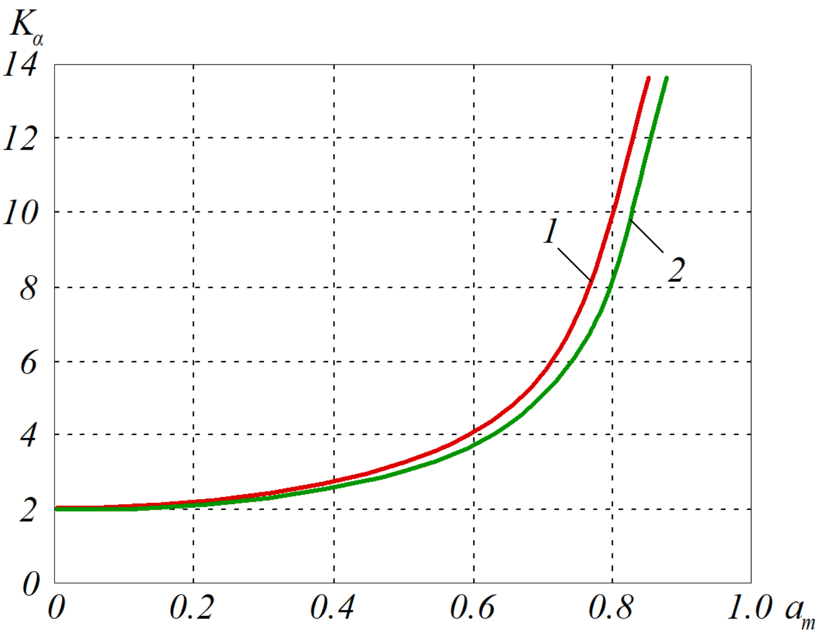

Figure 2. Dependence of magnetic loss increase coefficients on electromagnetic asymmetry: 1 – dependence $K_{\alpha n} = f(a_m)$;, 2 – dependence $K_{\alpha 1} = f(a_m)$.

Calculation of the third term of the harmonic series λ_n significantly increases the accuracy of the calculation. The error $\gamma_{\alpha 2}$ in determining losses by the coefficient $K_{\alpha 2}$ does not exceed 2% with asymmetry up to 80% and increases to 8 + 10% with an increase in electromagnetic asymmetry up to 90% (figure 3).

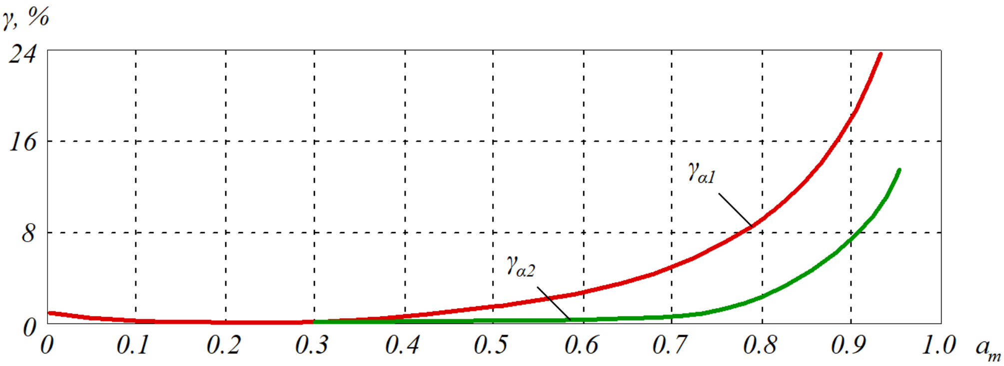

Figure 3. Change in the relative errors of the calculation of magnetic losses from groove harmonics of the field by coefficients.

Let us determine the specific magnetic losses in steel from the first groove harmonic of induction when the electric motor is operating in the phase-disconnected mode, substituting the expression for the spatio-temporal distribution of the groove frequency induction in (4) for the single-phase mode, taking into account the full distribution λ_n:

$$P'_{mgup} = K_n \cdot \frac{1}{2\pi \cdot T_n} \cdot \int_0^{2\pi} \int_0^{T_n} B^2_{fup}(\varphi, t) d\varphi \cdot dt. \tag{12}$$

Opening the brackets and integrating in a similar way, obtain the final expression for specific magnetic losses in steel from the first (upper) slot harmonic of induction in the form:

$$P'_{mgup} = \frac{1}{32} \cdot K_n \cdot (\lambda_0 \cdot \lambda_{j1} \cdot F_f)^2 \cdot \left(1 + \frac{1}{2} \cdot \lambda_{i1}^2\right) \cdot K_{\alpha n}, \tag{13}$$

where F_f is the magnetizing force when working on two phases; $K_{\alpha n}$ is the coefficient of electromagnetic asymmetry.

Thus, the nature of the dependence of the specific magnetic losses in steel on the groove harmonics of induction when the machine is operating in the mode with a disconnected phase is similar to the nature of this dependence for the three-phase mode and is determined by the type of function $K_{\alpha n} = f(a_m)$.

The quantitative ratio of losses during the operation of the electric motor in three-phase mode and in the mode with a disconnected phase can be estimated through the coefficient of proportionality of losses:

$$P'_{mgup} = K_f \cdot P_{mgup}, \tag{14}$$

where K_f is the proportionality factor $K_f = \frac{P'_{mgup}}{P_{mgup}}$; I_{vf} is the phase current in the phase-disconnected mode; I_{tf} is the phase current in three-phase mode; W is the the number of turns in a phase; k_o is the winding ratio.

Assuming that the phase resistance complexes at the fundamental frequency are approximately equal and the linear voltage to the root of three is greater than the phase voltage, obtain:

$$K_f = \frac{2}{3} \cdot \left(\frac{\sqrt{3}}{2}\right)^2 = \frac{1}{2}. \tag{15}$$

In a similar way, the specific magnetic losses from the lower groove harmonic of the induction, which varies in time with the frequency ω_n , can be calculated for both modes of operation of the machine. The total specific magnetic losses from the groove fields of the first order will be equal to the doubled value of P_{mgup} and P'_{mgup}.

Electromagnetic asymmetry significantly affects the nature of the distribution of the magnetic field in the air gap of the electric machine. In the presence of non-symmetry, the amplitudes of groove harmonics of magnetic induction increase.

The increase in the amplitude of the magnetic induction of higher harmonics of the magnetic field causes a sharp increase in magnetic losses from groove harmonics with an increase in electromagnetic asymmetry in accordance with the dependence $K_{\alpha n} = f(a_m)$. A significant increase in additional losses with an increase in electromagnetic asymmetry is also confirmed by a number of experimental studies.

The groove harmonic components of the magnetic field in the air gap induce electromotive force in the stator windings with frequencies ω_n.

In the conductor of each groove of the stator winding, an electromotive force of the groove frequency is induced, which is proportional to the change in induction. Accordingly, the square of the electromotive force will be proportional $B_n^2(\varphi, t)$ and proportional to the pulsation losses in the steel from the groove harmonics of induction P_{mgn} in the elementary volume of the groove zone near the k-th groove. Then the sum of the squares of the electromotive force in the conductors of all the slots of the stator winding will be proportional to the total magnetic losses of the electric machine from the slot harmonics of the field in the gap, and since the level of pulsation losses depends on the degree of electromagnetic asymmetry, the value will, other things being equal, be proportional to the energy level of the slot harmonics and will by some asymmetry function.

The dependence of the magnetic losses of the slot induction field from the similar dependence in the three-phase mode differs by a constant volume factor by summing the squares of the

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electromotive force of the slot frequency, given in all three phases of the stator winding, when each of them is sequentially disconnected, it is possible to obtain an indirect diagnostic parameter, that is a function of the unevenness of the electromagnetic system, since in the case of the specified summation, all n grooves of the stator winding are taken into account, which is similar to the integration over the stator boring circle. The degree of change of the obtained parameter with increasing electromagnetic asymmetry is determined by the nature of the dependence of pulsating magnetic losses on the asymmetry of the electromagnetic system.

The electromotive force of the groove frequency arising in the coil of the stator winding, which contains W turns, the sides of which lie in the grooves with angular coordinates φ_k and φ_n is defined as the time derivative of the flux linkage:

$$e_{kn}(t) = -\frac{d\psi_n}{dt}, \tag{16}$$

where ψ_n is the magnetic flux and flux coupling of toothed harmonics with turns of the stator winding.

In its general form, this expression can be given by the formula of harmonic oscillation:

$$e_{kn}(t) = E_{kn} \cdot \sin(\omega_{up} \cdot t - Q_{kn}); \tag{17}$$

$$E_{kn} = \sqrt{\left(\sum_{i=1}^{18} E_i \cdot \cos Q_i\right)^2 + \left(\sum_{i=1}^{18} E_i \cdot \sin Q_i\right)^2}; \tag{18}$$

$$\begin{cases} \arctan = \dfrac{\sum\limits_{i=1}^{18} E_i \cdot \sin Q_i}{\sum\limits_{i=1}^{18} E_i \cdot \cos Q_i}, & \text{if } \sum\limits_{i=1}^{18} E_i \cdot \sin Q_i \neq 0; \sum\limits_{i=1}^{18} E_i \cdot \cos Q_i \neq 0; \\ \frac{\pi}{2}, & \text{if } \sum\limits_{i=1}^{18} E_i \cdot \sin Q_i = 0; \sum\limits_{i=1}^{18} E_i \cdot \cos Q_i > 0; \\ \frac{3\pi}{2}, & \text{if } \sum\limits_{i=1}^{18} E_i \cdot \sin Q_i = 0; \sum\limits_{i=1}^{18} E_i \cdot \cos Q_i < 0, \end{cases} \tag{19}$$

where E_i is the amplitudes of harmonic components of the electromotive force coil; Q_i is the initial phases of harmonic components of the electromotive force coil.

The total electromotive force induced in the disconnected phase without parallel branches can be found by summing the electromotive force of the turns that make up the phase winding.

When disconnecting the next phase and determining the electromotive force of the groove harmonic in its winding, the value ψ_f and coordinates of the distribution of turns change.

If the disconnected phase of the stator winding contains N parallel-connected coil groups, then the electromotive force of the groove harmonic phase is equal to:

$$e_f(t) = \frac{1}{N} \cdot \left[e_{r1}(t) + e_{r2}(t) + ... + e_{rn}(t)\right], \tag{20}$$

where $e_{rn}(t)$ is the electromotive force of coil groups, defined as the sum of the electromotive forces of the component turns.

In the case of mixed connection of coil groups in phase, the electromotive force of parallel sections is determined by expression (17) and then summed up with all groups connected in series.

The amplitude of the electromotive force of the groove harmonic of a separate phase of the stator winding can either increase with an increase in electromagnetic asymmetry ψ_α with respect to the distribution of the turns of a given phase, or decrease, while the sum of the squares of the electromotive force of the groove harmonic of all three phases uniquely increases with increasing α, reflecting an increase in pulsation losses at presence of asymmetry, close to quadratic in nature.

Thus, according to the proposed method, the energy level of higher harmonics can be estimated by the sum of the squares of the electromotive force of the groove harmonics, taken when each of the three phases of the stator winding is turned off sequentially when the tested machine is idling. In order to exclude the influence of saturation phenomena on the control result and to reduce current overloads of the electric motor when operating in the mode with a disconnected phase, the measurement must be carried out when the two working phases of the winding are powered with a reduced single-phase voltage.

To refine theoretical calculations near the extreme points of the range of asymmetry values, a technique for presenting the amplitude of groove harmonics of magnetic induction in an air gap with two-way groove through the Carter coefficient, taking into account its dependence on electromagnetic asymmetry, is proposed:

$$B_n = B_m - B_{\alpha v}, \tag{21}$$

where B_n is the amplitude of the groove harmonic of induction; $B_{\alpha v}$ is the average value of induction with electromagnetic symmetry; B_m is the maximum value of induction.

Coefficients determined by the ratio of the groove opening width to the gap size:

$$\gamma_1(\varphi) = \frac{\left[\frac{B_{s1}}{\delta(\varphi)}\right]^2}{5 + \frac{B_{s1}}{\delta(\varphi)}}; \tag{22}$$

$$\gamma_2(\varphi) = \frac{\left[\frac{B_{s2}}{\delta(\varphi)}\right]^2}{5 + \frac{B_{s2}}{\delta(\varphi)}}. \tag{23}$$

Obtain the final expression for the amplitude of the groove harmonic of magnetic induction in an air gap with two-sided groove:

$$B_{\alpha v} = \frac{5 \cdot (t_{z1} \cdot B_{s2}^2 + t_{z2} \cdot B_{s1}^2) \cdot \delta(\varphi) + B_{s1} \cdot B_{s2} \cdot (t_{z1} \cdot B_{s2} + t_{z2} \cdot B_{s1} - B_{s1} \cdot B_{s2})}{\left[t_{z1} \cdot (5 \cdot \delta(\varphi) + B_{s1}) - B_{s1}^2\right] \cdot \left[t_{z2} \cdot (5 \cdot \delta(\varphi) + B_{s1}) - B_{s2}^2\right]}; \tag{24}$$

Using the method of determining the electromotive force, will obtain a general final expression for one phase of the upper groove frequency of the first order in the form of harmonic oscillation:

$$e_f(t) = E \cdot \sqrt{A_t^2 + B_t^2} \cdot \sin\left[\omega_{up} \cdot t + \arctan\left(-\frac{A_f}{B_f}\right)\right]; \tag{25}$$

$$E = E_t = -\frac{3 \cdot \sqrt{2} \cdot \mu_0 \cdot I \cdot l_\delta \cdot D_c \cdot W^2 \cdot k_b \cdot \omega_{up}}{4 \cdot \pi \cdot \delta_0 \cdot N_k \cdot p}; \tag{26}$$

$$A_f = \sum_{N=1}^{N_k} \int_{\varphi_k N_f}^{\varphi_n N_f} [k_\delta(\varphi) - 1] \cdot \sin(Z_2 + p) \cdot \varphi \cdot d\varphi, \tag{27}$$

where D_c is the stator diameter; N_k is the number of turns in the phase.

Accordingly, for the mode of operation of an asynchronous electric motor with a disconnected phase:

$$E = E_f = -\frac{\sqrt{6} \cdot \mu_0 \cdot I \cdot l_\delta \cdot D_c \cdot W^2 \cdot k_b \cdot \omega_{up}}{2 \cdot \pi \cdot \delta_0 \cdot N_k \cdot p}; \quad (28)$$

$$A_f = \sum_{N=1}^{N_k} \int_{\varphi_k N_f}^{\varphi_n N_f} [k_\delta(\varphi) - 1] \cdot \cos(p \cdot \varphi - \psi_f) \cdot \sin Z_2 \cdot \varphi \cdot d\varphi, \quad (29)$$

$$B_f = \sum_{N=1}^{N_k} \int_{\varphi_k N_f}^{\varphi_n N_f} [k_\delta(\varphi) - 1] \cdot \cos(p \cdot \varphi - \psi_f) \cdot \cos Z_2 \cdot \varphi \cdot d\varphi. \quad (30)$$

The dependence of the electromotive force of the groove harmonic of individual phases and the sum of the squares of their amplitudes on the magnitude of the electromagnetic asymmetry was calculated on an electronic computer. The calculation algorithm is built on the basis of the above mathematical apparatus using the given expressions.

As expected, the graphical form of the theoretical dependence of the sum of the squares of the electromotive force of the groove harmonic on the electromagnetic asymmetry, calculated according to the given mathematical model, is similar to the dependence $K_{en} = f(e)$.

The proposed technique allows determining the energy levels of higher harmonics not only taking into account the value of absolute and relative asymmetry, but also taking into account the direction in space of the plane of asymmetry in relation to the distribution of the stator windings.

The initial value for determining the spatial angle of the direction of the plane of asymmetry is obtained from the expression of the electromotive force of the groove harmonic from any disconnected phase of the stator winding, assuming that α, δ_0, E_{nA} are the values obtained by the expressions:

$$E_{nA} = E \cdot \sqrt{A_A^2 + B_A^2}; \quad (31)$$

$$A_A^2 + B_A^2 = \frac{E_{nA}^2}{E^2}, \quad (32)$$

where E is the general constant that does not depend on φ and t; A_A, B_A are the sums of definite integrals.

The algorithm for calculating the dependence of the electromotive force of the groove harmonic on the electromagnetic asymmetry is presented in (figure 4).

By replacing and introducing a new variable and bringing similar terms, will finally get the equation in the canonical form:

$$x^4 + a \cdot x^3 + b \cdot x^2 + c \cdot x + d = 0; \quad (33)$$

$$a = \frac{2 \cdot (A \cdot B + C \cdot D)}{A^2 + D^2}; \quad (34)$$

$$b = \frac{2 \cdot A \cdot M + B^2 + C^2 - D^2}{A^2 + D^2}; \quad (35)$$

$$c = \frac{2 \cdot (B \cdot M + C \cdot D)}{A^2 + D^2}; \quad (36)$$

$$d = \frac{M^2 - C^2}{A^2 + D^2}; \quad (37)$$

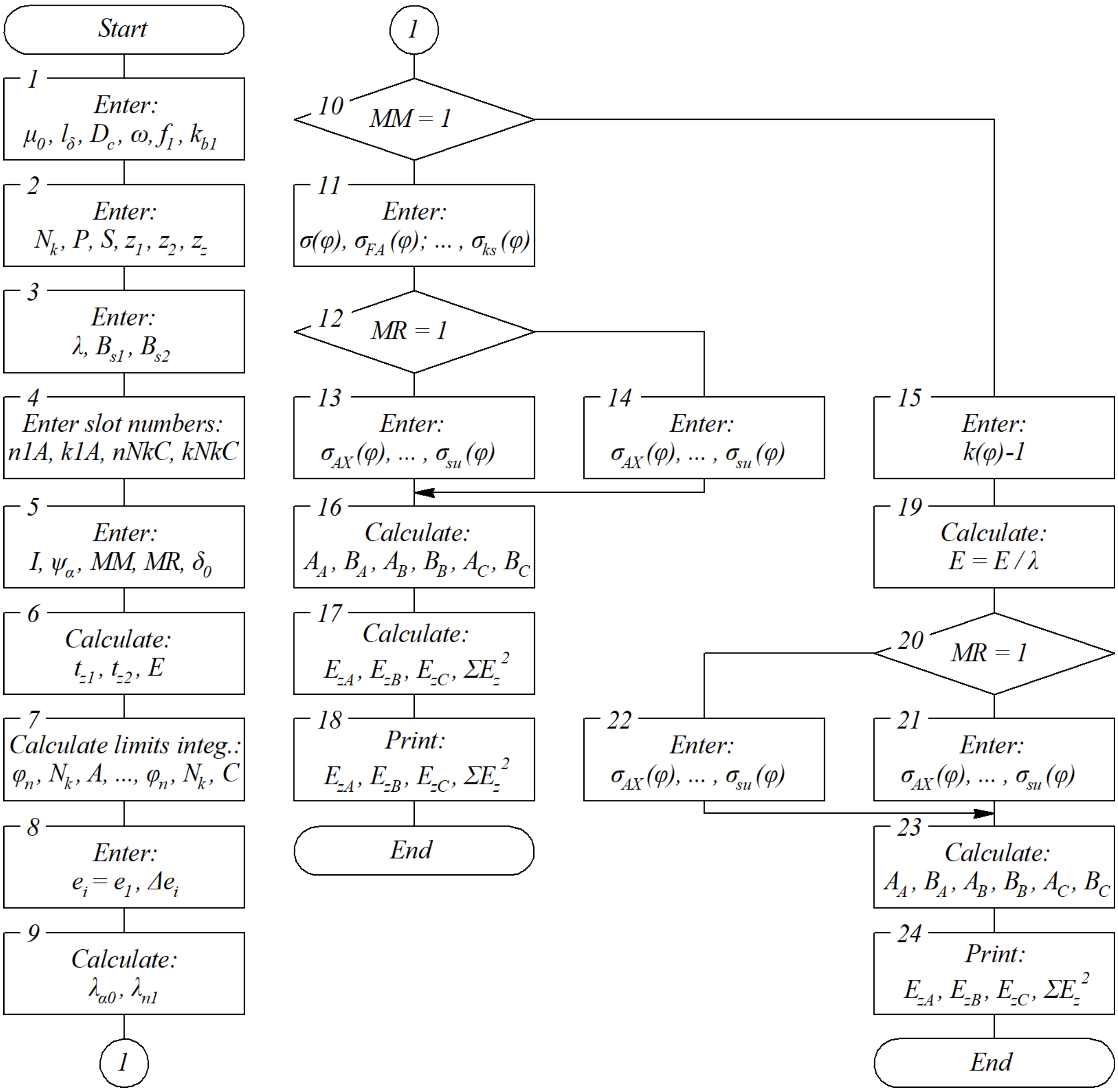

Figure 4. Calculation algorithm.

$$A = \lambda_{n1}^2 \cdot (C_2^2 + C_5^2 - C_3^2 - C_6^2); \tag{38}$$

$$B = \lambda_{\alpha 0} \cdot \lambda_{n1} \cdot (C_1 \cdot C_2 + C_4 \cdot C_5); \tag{39}$$

$$C = \lambda_{\alpha 0} \cdot \lambda_{n1} \cdot (C_1 \cdot C_3 + C_4 \cdot C_6); \tag{40}$$

$$D = 2 \cdot \lambda_{n1}^2 \cdot (C_2 \cdot C_3 + C_5 \cdot C_6); \tag{41}$$

$$C_1 = \sum_{N=1}^{N_k} \int\limits_{\varphi_k N_A}^{\varphi_n N_A} \sigma'_A(\varphi) \cdot \sin Z_2 \cdot \varphi \cdot d\varphi; \tag{42}$$

$$C_2 = \sum_{N=1}^{N_k} \int\limits_{\varphi_k N_A}^{\varphi_n N_A} \sigma'_A(\varphi) \cdot \cos\varphi \cdot \sin Z_2 \cdot \varphi \cdot d\varphi; \tag{43}$$

$$C_3 = \sum_{N=1}^{N_k} \int_{\varphi_k N_A}^{\varphi_n N_A} \sigma'_A(\varphi) \cdot \sin\varphi \cdot \sin Z_2 \cdot \varphi \cdot d\varphi; \tag{44}$$

$$C_4 = \sum_{N=1}^{N_k} \int_{\varphi_k N_A}^{\varphi_n N_A} \sigma'_A(\varphi) \cdot \cos Z_2 \cdot \varphi \cdot d\varphi; \tag{45}$$

$$C_5 = \sum_{N=1}^{N_k} \int_{\varphi_k N_A}^{\varphi_n N_A} \sigma'_A(\varphi) \cdot \cos\varphi \cdot \cos Z_2 \cdot \varphi \cdot d\varphi; \tag{46}$$

$$C_6 = \sum_{N=1}^{N_k} \int_{\varphi_k N_A}^{\varphi_n N_A} \sigma'_A(\varphi) \cdot \cos Z_2 \cdot \sin\varphi \cdot \varphi \cdot d\varphi. \tag{47}$$

Thus, the desired angle ψ_α is determined through the roots of the reduced equations:

$$\psi_\alpha = \arccos x. \tag{48}$$

Of the four roots of expression (33), two are imaginary, and the two real roots give, respectively, a positive and a negative angle ψ_α calculated from the stator boring from the axis that coincides with the axis of the phase A winding.

The developed technique makes it possible to determine the levels of groove harmonic components in the phase windings of electric machines. These harmonics, depending on the connection scheme of the asynchronous motor windings (star, delta), the scheme and the load of the electrical network, spread over the electrical network, creating current harmonics or voltage harmonics. When analyzing asymmetric and non-sinusoidal modes at individual frequencies, various harmonic components arise, which leads to the emergence of specific current and voltage harmonics. All these phenomena must be taken into account when analyzing the modes of distribution networks.

The current level of development of electronic computers and their software allows to form mathematical models of the electrical network at the groove frequency in asymmetric modes, considering all its elements as three-phase. At the same time, equations in phase coordinates serve as mathematical models of both the network as a whole and its individual elements – equations containing mode parameters (voltages, currents, phase powers) as sought and set values.

Equations in phase coordinates refer to the electrical network, the elements of which are three-phase longitudinal and transverse branches. Longitudinal branches are contained in the schemes of substitution of sections of power transmission lines, three-phase windings of generators and transformers, transverse branches correspond to schemes of substitution of load nodes, transverse conductances of sections of overhead lines, branches of magnetization of transformers.

Each branch of the three-phase network is characterized by a matrix of own and mutual resistances of the phases:

$$[Z]_{ij}^F = \begin{bmatrix} Z_{aa} & Z_{ab} & Z_{ac} \\ Z_{ba} & Z_{bb} & Z_{bc} \\ Z_{ca} & Z_{cb} & Z_{cc} \end{bmatrix}_{ij}, \tag{49}$$

where the diagonal elements Z_{aa}, Z_{bb}, Z_{cc} reflect the active and inductive resistances of the respective phases, and non-diagonal resistances – the mutual induction between phases, and mode parameters – currents, voltages, electromotive forces of the phases.

$$[I]^F_{ij} = \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}_{ij}; \tag{50}$$

$$[U]^F_{ij} = \begin{bmatrix} U_a \\ U_b \\ U_c \end{bmatrix}_{ij}; \tag{51}$$

$$[E]^F_{di} = \begin{bmatrix} E_a \\ E_b \\ E_c \end{bmatrix}_{ij}. \tag{52}$$

In asymmetric emergency modes, loads are characterized by conductance matrices in the node to the ground:

$$[Y_H]^F = [Z^F_H]^{-1}. \tag{53}$$

In non-symmetric operating modes (non-linear model), the load conductivity matrices (53) are kept unchanged only at the step of the iteration process and are adjusted during the iterations in such a way that the total consumed power of the three phases becomes equal to the set power at the node.

The component equations of the elements of a three-phase network in phase values have the form:

- for longitudinal branches:

$$[Z]^F_{ij} \cdot [I]^F_{ij} = \left([U]^F_i - [U]^F_j\right); \tag{54}$$

- for transverse branches:

$$[Z]^F_{Hi} \cdot [I]^F_{Hij} = [U]^F_i; \tag{55}$$

- for branches with a source of electromotive force:

$$[Z]^F_{di} \cdot [I]^F_{di} = \left([U]^F_{di} - [E]^F_{di}\right). \tag{56}$$

These equations are a generalization of Ohm's law for a three-phase branch and differ from similar equations of elements of a single-phase circuit only in that resistances, currents, electromotive force and voltages of three-phase elements are not characterized by numbers, but by corresponding matrices.

Matrices of both longitudinal $[Z]_{ij}$, and transverse $[Z]_{i0}$ elements can be asymmetrical, symmetrical or, in a separate case (a group of single-phase elements), diagonal. All types of longitudinal and transverse asymmetry (non-transposed overhead lines, network elements operating with an incomplete number of phases, asymmetric loads, etc.) are reflected in the parameter matrices $[Z]$ of the corresponding elements.

A three-phase network can be matched by a graph, the branches of which correspond to three-phase branches, and the nodes to three-phase nodes. Then, for three-phase circuits and three-phase nodes, Kirchhoff's laws can be represented in the form:

$$\sum_{i=1}^{N} [I]^F_{ij} = 0; \sum_{i=1}^{N_k} [\Delta U]^F_{ij} = 0. \tag{57}$$

where $[I]_{ij}$ is the the currents in the branches adjacent to the three-phase node; $[U]_{ij}$ is the voltage drop on the three-phase branches forming a closed circuit in the three-phase network.

If for all independent three-phase nodes of the electrical networidraw up the current balance equation, solve the component equations of the three-phase branches adjacent to each of the nodes with respect to the currents and substitute them into the first of the equations, then for a network containing n independent three-phase nodes, get the system of equations of the electrical network in the asymmetric stationary mode in phase coordinates:

$$\begin{bmatrix} Y_{11} & Y_{12} & ... & Y_{1n} \\ Y_{21} & Y_{22} & ... & Y_{2n} \\ ... & ... & ... & ... \\ Y_{n1} & Y_{n2} & ... & Y_{nn} \end{bmatrix}^F \cdot \begin{bmatrix} U_1 \\ U_2 \\ ... \\ U_n \end{bmatrix}^F = \begin{bmatrix} J_1 \\ J_2 \\ ... \\ J_n \end{bmatrix}^F . \tag{58}$$

The elements of this system of equations are the 3×3 matrices of the own $[Y_{ii}]$ and mutual $[Y_{ij}]$ conductances of three-phase nodes, the vectors of phase voltages in the nodes of the three-phase network $[U_i]$ and set currents $[J_i] = [Y_i] \cdot [E_i]$ in the nodes of the connection of generating elements.

All asymmetric emergency damage in the electrical network (disconnection of phases, short circuits of individual phases to each other and to the ground, etc.) can be displayed quite simply when forming nodal equations, taking into account the corresponding commutations in nodes and branches of a three-phase network. Moreover, the presence of several asymmetric damages does not lead to any complications in the algorithms for forming and solving nodal equations compared to the case of local damages. Therefore, mathematical models based on equations in phase coordinates are more flexible and universal, applicable for the analysis of non-symmetric modes of operation with both simple and complex asymmetry.

In the linear model of the network (when applying loads with constant phase resistances Z_n = const), the phase voltages in the nodes of the network in the asymmetric mode under consideration are determined by a one-time solution of the equations, in the non-linear model (with the specified powers consumed and generated in the network nodes) the phase voltages are refined during of the iterative process until the sum of the powers of the three phases in each node of the network becomes equal to the given value. It was established that the levels of groove harmonics are determined by the structure and modes of the electrical network, the geometry of the groove zones of the air gap of the electric machine, and its magnetic properties. Theoretical propositions have been confirmed by experimental studies.

3. Conclusions

A method of calculating currents and electromotive force of the groove frequency of rotary electric machines for active-adaptive networks has been developed. Calculations are based on the analysis of the electromagnetic field of the electric machine and methods of calculating non-symmetrical and non-sinusoidal modes of distribution electric networks (phase coordinates method). It was established that the levels of groove harmonics are determined by the structure and modes of the electrical network, the geometry of the groove zones of the air gap of the electric machine, and its magnetic properties.

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References

[1] Gundebommu S L, Hunko I, Rubanenko O and Kuchanskyy V 2020 Assessment of the Power Quality in Electric Networks with Wind Power Plants *2020 IEEE 7th International Conference on Energy Smart Systems (ESS)* pp 190–194 URL https://doi.org/10.1109/ESS50319.2020.9160231

[2] Nerubatskyi V, Plakhtii O and Hordiienko D 2021 Control and Accounting of Parameters of Electricity Consumption in Distribution Networks *2021 XXXI International Scientific Symposium Metrology and Metrology Assurance (MMA)* pp 1–4 URL https://doi.org/10.1109/MMA52675.2021.9610907

[3] Lin C, Han G, Du J, Xu T and Peng Y 2021 *IEEE Transactions on Intelligent Transportation Systems* **22** 3697–3706 URL https://doi.org/10.1109/TITS.2020.3028990

[4] Samadi A and Chabanloo R M 2019 Adaptive coordination of overcurrent relays in active distribution networks utilizing a multi-objective optimization approach *2020 14th International Conference on Protection and Automation of Power Systems (IPAPS)* pp 20–25 URL https://doi.org/10.1109/IPAPS49326.2019.9069388

[5] Huang T, Tan L, Wang R, Li C, Li H and Huang X 2020 Research on Suppression of Higher Harmonics in Wireless Power Transmission System *2020 IEEE PELS Workshop on Emerging Technologies: Wireless Power Transfer (WoW)* pp 228–232 URL https://doi.org/10.1109/WoW47795.2020.9291304

[6] Babu M, Roy P and Banerjee R 2020 Harmonic Analysis for Power Loss Minimization in Radial Distribution System *2020 11th International Conference on Computing, Communication and Networking Technologies (ICCCNT)* pp 1–5 URL https://doi.org/10.1109/ICCCNT49239.2020.9225526

[7] Syvokobylenko V F and Lysenko V A 2021 Use of higher harmonics in currents and voltages for phase-to-ground fault protection in medium voltage networks *2021 IEEE 2nd KhPI Week on Advanced Technology (KhPIWeek)* pp 172–176 URL https://doi.org/10.1109/KhPIWeek53812.2021.9569967

[8] Plakhtii O, Nerubatskyi V, Scherbak Y, Mashura A and Khomenko I 2020 Energy efficiency criterion of Power Active Filter in a three-phase network *2020 IEEE KhPI Week on Advanced Technology (KhPIWeek)* p 165–170 URL https://doi.org/10.1109/KhPIWeek51551.2020.9250073

[9] Bebikhov Y V, Egorov A N and Semenov A S 2020 How Higher Harmonics Affect the Electrical Facilities in Mining Power Systems *2020 International Conference on Industrial Engineering, Applications and Manufacturing (ICIEAM)* pp 1–7 URL https://doi.org/10.1109/ICIEAM48468.2020.9111965

[10] Kotsur M I, Bezverkhnia Y S, Yarymbash D S and Kotsur I M 2022 *Electrical Engineering and Power Engineering* (2) 18–29 URL https://doi.org/10.15588/1607-6761-2022-2-2

[11] Dalai S K, Sahu R and Tripathy C S 2020 Harmonic Mitigation in Single-Phase Grid Connected Photovoltaic System Using SPWM Inverter *2020 International Conference on Computational Intelligence for Smart Power System and Sustainable Energy (CISPSSE)* p 1–6 URL https://doi.org/10.1109/CISPSSE49931.2020.9212280

[12] Das A, Anand S and Sahoo S R 2020 Availability Based Load Harmonic Compensation Using PV Inverter *2020 IEEE International Conference on Power Electronics, Drives and Energy Systems (PEDES)* p 1–6 URL https://doi.org/10.1109/PEDES49360.2020.9379672

[13] Xu Q, Ma G, Ding K and Xu B 2020 *IEEE Access* **8** 174489–174494 URL https://doi.org/10.1109/ACCESS.2020.3025377

[14] Li P, Zhang C, Wu Z, Xu Y, Hu M and Dong Z 2020 *IEEE Transactions on Smart Grid* **11**(3) 2245–2256 URL https://doi.org/10.1109/TSG.2019.2950120

[15] Gujar N S, Trivedi N, Gupta V and Sharma S 2018 Development of embedded system for monitoring of real time harmonics *2018 3rd IEEE International Conference on Recent Trends in Electronics, Information & Communication Technology (RTEICT)* p 222–227 URL https://doi.org/10.1109/RTEICT42901.2018.9012413

[16] Yaghoobi J, Zare F and Rathnayake H 2021 *IEEE Journal of Emerging and Selected Topics in Power Electronics* **9**(3) 2868–2880 URL https://doi.org/10.1109/JESTPE.2020.3028312

[17] Al-Rawashdeh A Y, Dalabeeh A, Al-Zeyod A, Samarah A, Qaryouti G and Albarbarawi O 2020 *Bulletin of Electrical Engineering and Informatics* **9**(4) 1677–1684 URL https://doi.org/10.11591/eei.v9i4.1565

[18] Cheng M, Zhu X, Wang Y, Wang R and Wang W 2020 *IEEE Transactions on Energy Conversion* **35**(1) 279–291 URL https://doi.org/10.1109/TEC.2019.2948974

[19] Hu Y, Xu J, Qian H, Bian S and Xie S 2020 Robustness and Harmonics Suppression of Grid-Connected Inverters with Different Grid Voltage Feedforward Compensations in Weak Grid *2020 IEEE 29th International Symposium on Industrial Electronics (ISIE)* p 779–784 URL `https://doi.org/10.1109/ISIE45063.2020.9152568`

[20] Nerubatskyi V, Plakhtii O and Hordiienko D 2022 Efficiency Analysis of DC-DC Converter with Pulse-Width and Pulse-Frequency Modulation *2022 IEEE 41st International Conference on Electronics and Nanotechnology (ELNANO)* p 571–575 URL `https://doi.org/10.1109/ELNANO54667.2022.9926762`

[21] Vadamalu R S and Beidl C 2021 *IEEE/ASME Transactions on Mechatronics* **26**(1) 381–392 URL `https://doi.org/10.1109/TMECH.2020.3022736`

[22] Gonzalez-Abreu A D, Osornio-Rios R A, Jaen-Cuellar A Y, Delgado-Prieto M, Antonino-Daviu J A and Karlis A 2022 *Energies* **15**(5) 1909 ISSN 1996-1073 URL `https://doi.org/10.3390/en15051909`

[23] Joseph S, Pandey S, Sarkar S and Joseph J 2021 *Nanophotonics* **10**(17) 4175–4207 URL `https://doi.org/10.1515/nanoph-2021-0387`

[24] Asci C, Sadeqi A, Wang W, Rezaei Nejad H and Sonkusale S 2020 *Scientific Reports* **10**(1) 1050 ISSN 2045-2322 URL `https://doi.org/10.1038/s41598-020-57773-6`

[25] Bykhovsky D 2022 *Energies* **15**(2) 653 URL `https://doi.org/10.3390/en15020653`

[26] Evestedt F, Pérez-Loya J J, Abrahamsson C J D and Lundin U 2021 *Electrical Engineering* **103**(1) 195–203 ISSN 1432-0487 URL `https://doi.org/10.1007/s00202-020-01069-5`

[27] Koteleva N I, Korolev N A and Zhukovskiy Y L 2021 *Energies* **14**(20) 6677 URL `https://doi.org/10.3390/en14206677`

[28] Jiang M, Tian J, Goh H H, Yi J, Li S, Zhang D and Wu T 2022 *Energy Reports* **8** 332–342 ISSN 2352-4847 The 2022 International Conference on Energy Storage Technology and Power Systems

[29] Ahmed M, Nahid-Al-Masood and Aziz T 2021 *Energy Reports* **7** 6273–6291 ISSN 2352-4847 URL `https://doi.org/10.1016/j.egyr.2021.09.072`

[30] Li J, Fang H, Liao C and Du J 2020 *IEEE Access* **8** 119071–119081 URL `https://doi.org/10.1109/ACCESS.2020.3001031`

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Method of operative determination of the stability of circulating water with regard to the release of $CaCO_3$

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Method of operative determination of the stability of circulating water with regard to the release of $CaCO_3$

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Abstract. Sediments on the technological surfaces of the recirculating water supply system (RWSS) of enterprises are considered. The kinetic equation for the activity concentration of the main sediment component – Ca^{2+} ions in circulating water (CW) is discussed. Based on this equation, expressions were obtained for the rate of formation of $CaCO_3$ from CW and the stability index of CW, which is expressed by the activity concentration of free Ca^{2+} ions not bound in $CaCO_3$. These values are determined by measuring parameters of the quality of CW and the mode of operation of the recirculating system, which are provided for by the regulations for the operation of the RWSS Current information on the value of the stability index makes it possible to calculate the rate of $CaCO_3$ precipitation and, if necessary, to develop quantitative parameters of operational measures to stabilize CW. The algorithm for calculating the stability index was applied to the RWSS of one of the HPPs, where softening of the feed water and bypass softening of CW are used. The calculated value of the index adequately reflects changes in the stability of the CW during variations in the operation mode of the RWSS. The stability index was used to calculate the parameters of CW acidification, which ensure the desired level of its stability.

1. Introduction

Today, the vast majority of large enterprises, thermal and nuclear power plants (HPPs, NPPs) are equipped with reversible water supply systems (RWSS). Almost 95% of water consumption there used for cooling of technological equipment. Considering the large consumption of cooling water (about 170,000 m^3/hour per 1000 MW unit), natural, untreated water is used for cooling. Such water is capable of releasing solid sediments (mainly $CaCO_3$ on process surfaces, in particular, on pipe systems (PS) of turbine condensers (TC) [1, 2].

The coefficient of thermal conductivity of sediments is ten times lower than that of the PS material, so that already at a thickness of (1.2-1.6) mm, the heat transfer coefficient of heat exchangers (HE) decreases by (30-40)%, and this leads to a decrease in the efficiency of power units by (0.5-1.2)% [3], excessive consumption of fuel by (1.5-3.5)% and the need to clean TCs, reducing the electrical load of the units.

Note that for a 1000 MW power unit, the corresponding annual electricity losses are (120÷245) million kWh, which roughly corresponds to the energy consumption of a city with a population of (40-80) thousand people. Excessive consumption of fuel at HPPs, along with economic losses, results in excessive emissions of heat, greenhouse gases, and harmful substances into the environment.

To reduce the intensity of sediments partial or complete softening of the feed water, adding of mineral acids to the water and dosing of sediment inhibitors are used. The effect of the inhibitors is associated with blocking the growth centers of $CaCO_3$ crystal nuclei, providing them with an additional charge and thus stabilizing the $CaCO_3$ dispersion, which is expressed in a decrease in the intensity of deposits on the PS of heat exchangers [4, 5].

2. Formulation of the problem

An important problem in the reagent stabilization of circulating waters of thermal power plants and nuclear power plants is the lack of reliable operational control of the ability of CW to form sediments.

The regulations [6] suggest using the Langelier index, LSI, or the CW supersaturation index with respect to $CaCO_3$, SI [7, 8]. The mentioned indices are represented by expressions:

- Langelier index:

$$LSI = \mathrm{pH} - \mathrm{pH}_s = -\lg \frac{(H)}{(H)_s}, \tag{1}$$

$(H)_s$ – activity concentration of hydrogen ions when the water system is in equilibrium with the environment; (H) – measured activity concentration.

Today pH measuring is not difficult, but the calculation of pH_s depends on the selected model of the bicarbonate system and does not always correspond to reality.

Because of this, pH_s are recommended to be determined experimentally [9].

It follows from formula (1) that if $LSI < 0$, there is an excess of hydrogen ions in the water system and it is corrosively active and capable of dissolving carbonate sediments. If $LSI > 0$, on the contrary, there is a lack of hydrogen ions in the system and it emits $CaCO_3$. Of course, at $LSI = 0$, the hydrocarbonate system (HCS) is stable.

Unfortunately, knowing the LSI, we do not get a quantitative assessment of the degree of deviation of the HCS from the balance. That is, the LSI provides qualitative information about the state of the HCS and does not directly indicate the quantitative characteristics of measures to correct the stability of the CW. In addition, if we are talking about the RWSS, the LSI is not directly related to the operation mode of the RWSS.

- Index of CW supersaturation in relation to $CaCO_3$: it is calculated by the formula,

$$SI = \frac{(\mathrm{Ca}^{2+}) \cdot (\mathrm{CO}_3^{2-})}{L_{\mathrm{CaCO}_3}}, \tag{2}$$

$(\mathrm{Ca}^{2+}), (\mathrm{CO}_3^{2-}), L_{\mathrm{CaCO}_3}-$ activity concentrations of calcium and carbonates ions and the solubility product of the $CaCO_3$.

It follows from the physical content of formula (2) that with $SI > 1$, there is an excess of carbonate and calcium ions in the water system and it can release $CaCO_3$. If $SI < 1$, on the contrary, there is a lack of ions in the system and it dissolves $CaCO_3$. Of course, at $SI = 1$, the hydrocarbonate system is stable. However, as in the case of the Langelier index, the SI calculation gives only qualitative information about the state of the HCS, this information refers to the CW and does not reflect its status as an element of the RWSS.

At NPPs, the following ratio is used to characterize the stability of the CW

$$\varepsilon \geq \frac{C_{\mathrm{Cl}}}{C_{\mathrm{Cl0}}} - \frac{Ht}{Ht_0}, \tag{3}$$

ε is a given value, for example, $0.1 \div 0.3$; Ht, Ht_0 is the total hardness of circulating water and feed water, the same for chloride concentrations $C_{\mathrm{Cl}}, C_{\mathrm{Cl0}}$.

The value of ε is mostly not substantiated, and the use of hardness ($Ca^{2+} + Mg^{2+}$) instead of Ca^{2+} concentration leads to additional errors (overestimation) of CW stability.

Therefore, today there is no generally accepted method for determining the quantitative degree of stability of CW, which could be directly used as a characteristic of the deviation of the state of CW from the equilibrium state, when a dynamic equilibrium is established in CW between the processes of $CaCO_3$ generation and its dissolution, and the rate of sediment growth is minimal (ideally, it goes to zero).

It is important that this method of determining the degree of stability of CW clearly depends on the regime parameters of RWSS and the quality of CW. Having such a parameter (by analogy with (1) and (2), we will call it the stability index), it would be possible to form an algorithm for calculating the doses of reagents or the level of softening of the feed water depending on the degree of deviation from the equilibrium state. It would be most convenient to obtain this value on the basis of operational information about the state of CW based on the data of regular measurements of RWSS regime parameters and CW quality parameters conducted at enterprises, in particular at HPPs and NPPs.

The formulation of the methodology for calculating the CW stability index in relation to the re-lease of $CaCO_3$, and the application of the results of its determination in the real conditions of a specific TPP are considered in this work.

3. Calculation method

It was shown in [1] that the main component of the sediments is calcium carbonate $CaCO_3$. Accordingly, the procedure for determining the stability of CW should be based on monitoring the dynamics of the concentration of Ca^{2+} ions in CW. To obtain the kinetic equation for the concentration of Ca^{2+}, we use the balance of the number of moles of calcium in the circulating water of the RWSS and take into account that the concentration of calcium changes in the CW due to water exchange, water evaporation, and the formation of $CaCO_3$. Other channels of changes in the concentration of Ca^{2+} ions in CW are neglected.

Let us denote the rate of $CaCO_3$ formation by $R(t), \mathrm{mole}/(\mathrm{dm}^3 \cdot \mathrm{s})$, then for a simple RWSS we can write an expression for the rate of change of the activity concentration of Ca^{2+} ions in CW,

$$\frac{\mathrm{d}C(t)}{\mathrm{d}t} = \frac{1}{T_f(t)} \cdot \left[C_0(t) - \frac{C(t)}{\phi(t)}\right] - R(t), \tag{4}$$

$$\phi(t) = \frac{k(t)}{1 - k(t) \cdot T_f(t) \cdot \frac{\mathrm{d}}{\mathrm{d}t} \ln\left[C_{\mathrm{Cl}}(t)\right]}; \quad T_f(t) = \frac{V(t)}{Q_f(t)}, \tag{5}$$

$C_0(t), C(t)$ – activity concentrations of calcium ions in feed and circulating waters; $Q_f(t), V(t)$– feed water flow rate and water volume of the RWSS; $T_f(t)$ is the time of filling the RWSS with feed water. The parameter $\phi(t)$ in formula (4) is called the dynamic factor. As it follows from (5), for the stationary mode of operation of the RWSS, when $\frac{\mathrm{d}}{\mathrm{d}t} \ln\left[C_{\mathrm{Cl}}(t)\right] \approx 0$, this value approaches the concentration coefficient $k = \frac{C_{\mathrm{Cl}}}{C_{\mathrm{Cl0}}}$ of circulating water and is determined by the standard method by measuring the concentration of chloride ions.

Let's transform (4) to the form that shows how Ca^{2+} ions are distributed in CW,

$$C_0(t) \cdot \phi(t) = T_f(t) \cdot R(t) \cdot \phi(t) + T_f(t) \cdot \frac{\mathrm{d}C(t)}{\mathrm{d}t} \cdot \phi(t) + C(t). \tag{6}$$

The left part (6) is the activity concentration of calcium ions, what it would be in CW in the absence of $CaCO_3$ formation. The first term on the right is part of the concentration of calcium ions that have changed to the state of $CaCO_3$ during the time T_f – the stay of the feed water in the RWSS. The third term is the excess (that exists at the moment of time t) activity concentration of free calcium ions in CW, which can be determined by any available method.

After dividing both sides of (6) by $C_0(t) \cdot \phi(t)$, let's convert it to the form

$$G_{inst}(t) + \Psi_{st}(t) = 1; \tag{7}$$

$$G_{inst}(t) = \frac{T_f(t) \cdot R(t)}{C_0(t)}; \quad \Psi_{st}(t) = \frac{C(t)}{C_0(t) \cdot \phi(t)} \cdot \left[1 + \phi(t) \cdot T_f(t) \cdot \frac{\mathrm{d}\,[\ln C(t)]}{\mathrm{d}t}\right] \tag{8}$$

The first expression (8) is the fraction of calcium ions of the feed water, which during its stay in the RWSS passes into the state of $CaCO_3$. Let's call this value the factor of instability of water with respect to the precipitate of $CaCO_3$.

The second expression (8) is the fraction of calcium ions from the feed water that does not change to the $CaCO_3$ state during its stay in the RWSS. It is natural to consider this value as an index of the stability of circulating water in relation to the release of $CaCO_3$. For a stationary state, when $dC(t)/dt = 0$, the stability index takes the form

$$\Psi_{st}(t) = \frac{C(t)}{C_0(t) \cdot \phi(t)}; \quad \phi(t) = \frac{C_{\mathrm{Cl}}(t)}{C_{\mathrm{Cl0}}(t)}, \tag{9}$$

it is equal to the fraction of the concentration of free Ca^{2+} ions remaining in the CW relative to the amount of Ca^{2+} ions that would be in the CW in the absence of $CaCO_3$ formation.

For transient processes controlled by external conditions, provided that the value of the second term in square brackets (8) is proportional to unity

$$|\ \phi(t) \cdot T_f(t) \cdot \frac{\mathrm{d}\,[\ln C(t)]}{\mathrm{d}t}\ | \approx 1, \tag{10}$$

the value of the stability index will depend on the sign (10) and will reflect the influence of external factors unrelated to the formation of $CaCO_3$. That is, the stability index introduced by us adequately describes the process of carbonate release for the operating mode of RWSS close to stationary.

By the way, having determined the stability index, we can use (8) to calculate the rate of formation of $CaCO_3$ from circulating water,

$$R(t) = [1 - \Psi_{st}(t)] \cdot \frac{C_0(t)}{T_f(t)} = [1 - \Psi_{st}(t)] \cdot \frac{C_0(t) \cdot Q_f(t)}{V(t)} \tag{11}$$

Note that in the case of the use of bypass softening of CW such that a part of CW is removed from the circulation flow, softened in a special bypass clarifier and returned to the circulation flow again, the expression for calculating the stability index changes,

$$\Psi_{st}(t) = \frac{C(t)}{C_0(t) \cdot \phi(t)} \cdot \left\{1 + \phi(t) \cdot P_{bp}(t) \cdot [1 - b_{bp}(t)] + \phi(t) \cdot T_f(t) \cdot \frac{\mathrm{d}\,[\ln C(t)]}{\mathrm{d}t}\right\} \tag{12}$$

$$P_{bp}(t) = \tfrac{Q_{bp}(t)}{Q_f(t)}, \quad b_{bp}(t) = \tfrac{C_{bp}(t)}{C(t)},$$

$Q_{bp}(t)$ – water consumption through the bypass clarifier, $C_{bp}(t)$ – activity concentration of calcium ions at the outlet of the bypass clarifier.

The characteristic feature of bypass clarifier that is important when using sediment inhibitors is the absorption of a part of the inhibitors from CW. Moreover, the concentration of inhibitors can decrease in the CW stream by (30-40)%. Therefore, the loss of inhibitors must be compensated for by a corresponding increase in their dosage in circulating water.

4. Application example

The proposed methodology for calculating the CW stability index for the formation of $CaCO_3$ will be applied to characterize the CW condition and minimize the growth rate of CW precipitation at one of Ukraine's HPPs. For this purpose, we use the CW parameters that were measured in accordance with the operating regulations of the RWSS, namely:

$$\left(\mathrm{Ca}^{2+}\right)_0, \quad \left(\mathrm{Ca}^{2+}\right), \quad \left(\mathrm{Cl}^{-}\right)_0, \quad \left(\mathrm{Cl}^{-}\right), \quad Q_f, \quad V \tag{13}$$

Taking into account the high hardness of natural water $(9.5 - 14.5)\frac{\mathrm{mg-eq}}{\mathrm{dm}^3}$ before feeding into the RWSS, approximately 85% of the feed water is softened so that its calcium hardness at the entrance to the RWSS was $\approx 2.1\frac{\mathrm{mg-eq}}{\mathrm{dm}^3}$, and in the CW reached $\approx (4.0 - 4.4)\frac{\mathrm{mg-eq}}{\mathrm{dm}^3}$, with a concentration factor of $k = 3.0 - 3.5$.

During the 300-day RWSS studies, see figure 1 it worked in standard mode (without bypass) with an inhibitor concentration of $C_i = 3.5\frac{\mathrm{mg}}{\mathrm{dm}^3}$. The stability index before turning on the bypass calculated according to formula (9) was in the range of $\Psi_{st} \approx (0.60 - 0.63)$, which was clearly insufficient for the normal operation of power units. The turbine condensers had to be cleaned every 3 months, and due to the need to reduce the electrical load during cleaning, the station suffered significant losses. To increase the current stability, starting from the 300th day of observation, the bypass clarification of the CW with the following parameters was included:

$$P_{bp} = 0.18, \quad b_{bp} = 0.4, \quad \phi = 3.2, \quad C_0 = 2.1\frac{\mathrm{mg-eq}}{\mathrm{dm}^3}, \quad C = 4.2\frac{\mathrm{mg-eq}}{\mathrm{dm}^3}.$$

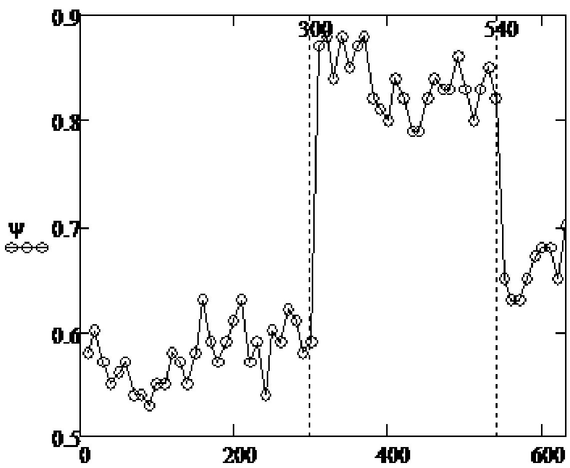

Figure 1. Dependence of CW stability index Ψ_{st} on the number of the measurement day. Vertical lines 300 and 540 indicate the moments of CW clarification switching on and the reduction of inhibitor dose.

The results of the calculation of the stability index according to formula (12) is shown in figure 1. We see that the use of bypass clarification of the CW increases the stability of CS up to 87% while maintaining the same inhibitor concentration in CW of $3.5\frac{\mathrm{mg}}{\mathrm{dm}^3}$.

Note that the expression for the stability index in the bypass mode, formula (12), allows us to calculate the amount of CW consumption for bypass required to ensure the desired level of stability.

After reaching $\Psi_{st} \approx 0.82 - 0.88$, the precipitation rate decreased by almost three times, which made it possible to clean TCs during scheduled preventive repairs.

In order to make sure of the effectiveness of choosing the right dose of the inhibitor and the adequacy of the algorithm for calculating the degree of stability, starting from the 540th day, the dose of the inhibitor was reduced by 30%. Accordingly, the calculated stability of CW also decreased by $\approx$ 30%. This indicates that the method of calculating the stability of CW adequately reflects the processes in CW.

The results presented here indicate the possibility of operational control of the stability of CW based on the data of regular measurements of its quality parameters and parameters of the operating mode of the RWSS.

5. An example of application for correcting the stability of CW with acid

Let's consider an alternative option of stabilizing CW by acidifying it, for example, with sulfuric acid. Assume that the CW stability after softening was 60%. Considering it insufficient, we calculate the amount of sulfuric acid dose that must be added to the feed water to achieve the desired level of stabilization $\max \Psi_{st} = 0.87$.

To do this, we take into account that each gram mole of the acid binds an equivalent number of calcium ions, that is, the expression for the desired value of the stability index is presented as

$$\max \Psi_{st} = \frac{1}{\phi \cdot C_0} \cdot (C + \Delta C) = \Psi_{st} + \frac{\Delta C}{\phi \cdot C_0}, \tag{14}$$

ΔC is the part of the concentration of Ca^{2+} ions that is bound by the acid, it is equal to the added concentration of the acid C_A in the CW; Ψ_{st} is the existing stability of CW before acidification.

From expression (14), we determine the concentration of the acid that must be added to CW, $\frac{\text{g-mole}}{\text{dm}^3}$,

$$C_A = C_0 \cdot \phi \cdot (\max \Psi_{st} - \Psi_{st}). \tag{15}$$

Considering that the amount of acid in CW due to concentration is ϕ times higher than in feed water, we get the acid concentration for feed water,

$$C_{A0} = C_0 \cdot (\max \Psi_{st} - \Psi_{st}). \tag{16}$$

According to (15), we find the mass concentration of sulfuric acid (100%), which must be added to the feed water,

$$C_{A0} = 2.1(0.86 - 0.6) \cdot 49 \ \frac{\text{mg}}{\text{dm}^3} = 26.8 \ \frac{\text{mg}}{\text{dm}^3} \approx 27 \cdot 10^{-3} \ \frac{\text{kg}}{\text{m}^3}$$

We compare it with the consumption of the inhibitor during simultaneous bypass (take into account the increase in the dose of the inhibitor by 1.4 times due to its absorption by the bypass clarifier),

$$C_{i0} = 1.4 \cdot C_i/k = 1.4 \cdot 3.5/3.2 = 1.53 \cdot 10^{-3} \ \frac{\text{kg}}{\text{m}^3}$$

We obtain that the mass concentration of the inhibitor is 17.6 times lower than that of the acid. That is, in this case, it might be more expedient to limit, after softening the feed water, its acidification instead of two procedures of adding an inhibitor and bypass softening.

The calculations presented here are intended to show how useful the concept of the stability index is, as it allows obtaining a quantitative level of stability of CW and simplifies the estimation of the number of reagents needed to achieve the desired level of stabilization of CW and makes it possible to compare stabilization options without much difficulty.

6. Conclusions

- To quantitatively characterize the degree of stability of CW, we suggest using the stability index. It has a clear physical meaning – it is equal to the relative part of the concentration of Ca^{2+} ions that remains free in the CW, not bound in calcium carbonate. The calculation procedure is also simple and clear.

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- It should be kept in mind that the stability index adequately describes the process of $CaCO_3$ formation in the case when there are no sharp changes in the concentration of Ca^{2+} ions in the RWSS, see (10), caused by external conditions (the established mode of operation of the RWSS).
- For operational control and determination of the level of stability of CW, it is necessary to measure the parameters of water quality and mode of operation of the RWSS in the established mode of operation of the RWSS: $\left(\mathrm{Ca}^{2+}\right)_0$, $\left(\mathrm{Ca}^{2+}\right)$, $\left(\mathrm{Cl}^{-}\right)_0$, $\left(\mathrm{Cl}^{-}\right)$, Q_f, V.
- It follows from expression (12) that the rate of formation of $CaCO_3$ is proportional to the concentration of calcium ions in the feed water, its consumption, and is inversely proportional to the water volume of the RWSS. In other words, RWSS with a larger water volume are less sensitive to contamination of heat exchangers than with a smaller one. In particular, this concerns to RWSS with cooling ponds.

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References

[1] Kochmarskii V Z and Pospelov D N 1990 *Prevention and cleaning of contaminated heat exchangers-coolers of power plants and industrial enterprises* (Znanie)
[2] Antonova N L, Kanyuk G Y, Pogonina T E, Mikhailovsky D M, Omelchenko L N and Fokina N F 2012 *Eastern European journal of advanced technologies* **2/10(56)** 56–62
[3] Shelepov I G and Mikhaisky D V 2005 *Eastern European journal of advanced technologies* **3/2** 122–125
[4] Kellermeier M, Gebauer D, Melero-Garcia E, Drechsler M, Talmon Y, Kienle L, Colfen H, Garcia-Ruiz J M and Kunz W 2012 *Advanced Functional Materials* **22** 4301–4311 ISSN 1616-3028 URL https://doi.org/10.1002/adfm.201200953
[5] Shmandiy V, Bezdeneznych L, Kharlamova O, Svjatenko A, Malovanyy M, Petrushka K and Polyuzhyn I 2017 *Chemistry & Chemical Technology* **11** 242–246 ISSN 19964196, 19964196 URL https://doi.org/10.23939/chcht11.02.242
[6] 2013 Building regulations and rules. V.2.5-74:2013. External networks and structures. Basic provisions of design. Appendix G
[7] 1988 *Guidelines for the prevention of mineral and organic sediments in turbine condensers and their cleaning RD34.22.501-87 1988 (Official. edition)* (Moscow: SPO Soyuztehenergo)
[8] Alekseev L S and Chebysheva N V 1987 *Information Review of All-Union Research Institute of Construction Gosstroy* **3** 41
[9] 2007 Standard Test Method: Laboratory Screening Tests to Determine the Ability of Scale Inhibitors to Prevent the Precipitation of Calcium Sulfate and Calcium Carbonate from Solution (for Oil and Gas Production Systems) URL https://www.studocu.com/fr/document/ecole-nationale-superieure-du-petrole-et-des-moteurs/reservoir-eng/tm0374-sulfate-and-calcium-carbonate-from-solution/25588356

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Contradictions in electric power sector development: Ukraine versus EU

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Contradictions in electric power sector development: Ukraine versus EU

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Abstract. Ukraine strives to be a full member of the EU and competitive in its market space, including energy markets. However, the UA electric power sector lags behind the EU common one. To prove this input-output model of electricity flows was constructed, Sankey diagrams were built, and qualitative indicators were determined. Based on the Eurostat dataset we found contradictions in Ukrainian electric power sector development against the European common one from 1991 to 2020. Mainstream trends in EU electric power sector development are decarbonization, development of highly efficient cogeneration, increasing energy efficiency at all stages, decentralization, increasing energy dependency, and all-round electricity penetration. At the same time, key tendencies in the UA electric power sector development were: gas-coal switching, reducing quality and quantity of cogeneration, stable too-low energy efficiency, centralization, isolation and self-sufficiency, and deindustrialization. Comprehending these contradictions determines the way for achieving sustainability in the UA electric power sector after the war.

1. Introduction

The electric power sector development of Ukraine is considered in the context of its integration into the European energy space. The result of such integration will be the receipt of significant benefits by European and Ukrainian electricity consumers in terms of quality, reliability of supply and cheaper prices under the pressure of competition. For nowadays Ukraine is being a member of the Energy Community and since the mid-2019 the pro-European model of the electricity market has been implemented but it does so in a quasi-competitive way [1]. Since the February 24th, 2022 Ukrainian electric power system has been synchronized with the entire European one and since March 16th 2022 Ukrainian transmission system operator has become an observer member of ENTSO-E. Nevertheless that now the Ukrainian electric power grids technically fulfil the European rules, its electric power sector remains still outdated and its development is not following European trends. The shortcomings of the Ukrainian electric power sector cast doubt on its success in the competitive struggle in the open European space and require a solution to the problem of finding priority areas for its future development.

The problem of electric power sector development has been strongly exacerbated by the Russian invasion of Ukraine. Currently, it is impossible to analyze the damage of electric power sector due to cybersecurity requirements (all data are closed since the February, 24th 2022 3 p.m.). However by the estimation of BBC the Ukrainian electric system suffered more than 250 strikes and there is no one thermal or hydro power plant left that would not be damaged [2].

Regardless, it is needed to explore Ukrainian previous experience to rebuild the electricity power sector after the war according to European pillars without neglecting national interests.

It is possible to analyze the state and trends of the Ukrainian electric power sector in the European space by developing the input and output electricity flows and comparing Ukrainian trends with European common ones and determining their similarities and contradictions, pros and cons of their development.

The input–output model is widely used application for quantitative assessment interdependencies between different sectors of a national economy or different regional economies [3] and electricity is public used good by all without exception spheres of economy [4]. Chong et al is considered that the input–output model is a suitable method for analyzing complex network data structures and Sankey diagram is its visualization tool [5]. Historically it referred to Leontief input–output model 1936 [6] and Sankey diagram was firstly constructed Hohmann in 1949 [7]. Nowadays the Sankey diagram is pointing up inefficiencies and potential for savings in connection with resource use [8], analyzing the energy balance and energy efficiency of an energy system [9], programming data-processing method for mapping energy allocation Sankey diagram and introduced primary energy quantity converted factor to connect end-use energy consumption and primary energy consumption [10]. These methods are commonly used in other different fields [11–13], but in most cases, it is applied for analysis of the energy and greenhouse gas emission flows [14–17]. So, Eurostat has developed an Sankey diagram to build and customize general energy balance and the main energy flows of a certain territory [18], but it could not be decomposed by types of energy sources or energy carriers.

The aim of the research is to develop methodological support for the analysis of input-output electricity flows and compare key trends in the electric power sector development in Ukraine with the EU common ones. Its hypothesis is formulated as follow: existence of significant contradictions in the electric power sector development of Ukraine and the EU.

The rest of paper is organized as follows. Section 2 contains the materials and methods used for the construction of input-output model of electricity flows. Section 3 provides authors' key findings on the contradictions of the UA and EU electric power sector development. Section 4 presents a discussion and conclusions of these contradictions and also recommendations for solving them.

2. Methodology and data

So, comparative analysis of input-output electricity flows in Ukraine and the EU can be carried out on the basis of Sankey diagrams, which are possible to build using Power BI software (developed by Microsoft Corp. [19]). The dataset of the research is the Eurostat database [20], which is compiled with Regulation (EC) No 1099/2008 [21] and ensures the unification and comparability of data by the dimensions of the electric power system, energy sources and types of activity. The dataset includes the data from 1991 to 2020 for Ukraine and EU-27 (currently it is impossible to refresh data for Ukraine due to the cybersecurity requirements during the war-time). But the use developed input-output model of electricity flow will allow for quick updating of data and slicing them for time periods and countries. Constructed input-output model of electricity flows is depicted in figure 1, based on it the Sankey diagrams of the inputs and outputs electricity flows are built by the stages of the electric power system. Data validation of the input-output model of electricity flows is based on the thermodynamic laws of conservation energy which requires for all energy in the electric power chain from the supply of primary energy resources to the final electricity consumption must be allocated or lost.

Based on the developed input-output model of electricity flows, it is possible to determine qualitative indicators of the electric power sector development, which can be divided into 3 groups: energy efficiency, structural, and security and integration (table 1). All these indicators can also be calculated in the Power Bi software space using measures.

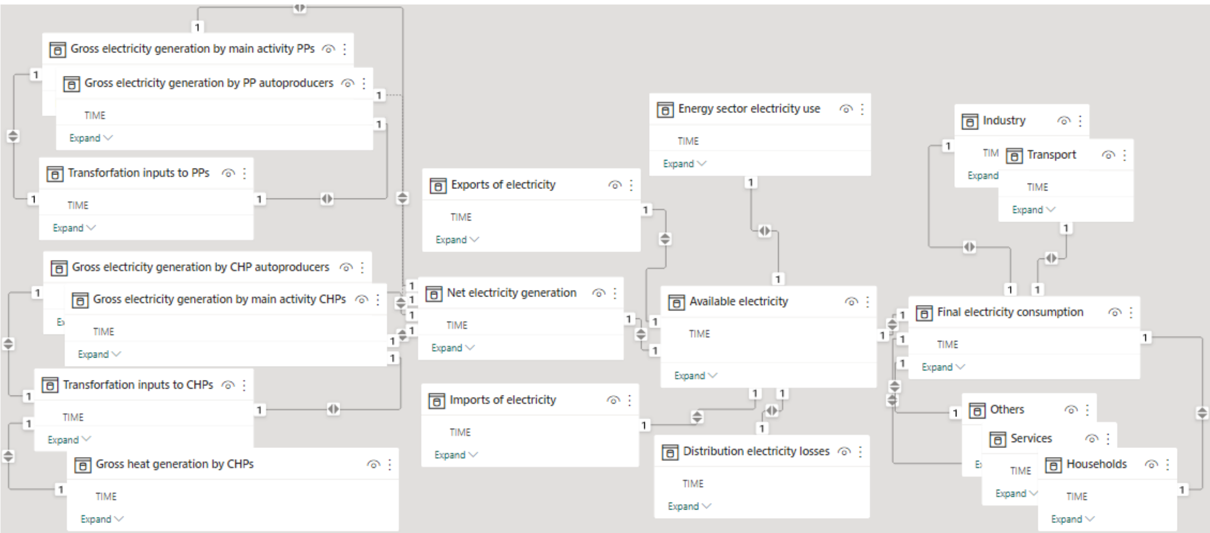

Figure 1. Input-output model of electricity flows in Power Bi software space: PP – power plant; CHP – combined heat and power plant.

Table 1. Qualitative indicators of the electric power sector development.

Group indicator	Indicator
Energy efficiency indicators	Energy efficiency of transformation by PPs Energy efficiency of transformation by CHPs Energy efficiency of generation Energy efficiency of transportation electricity General energy efficiency of electric power sector
Structural indicators	Share of RES in transformation inputs of electric power sector Share of OFF in transformation inputs of electric power sector Share of cogeneration in gross electricity generation Share of autoproducers in gross electricity generation Share of commercial electricity consumption Share of non-commercial electricity consumption
Security and Integration indicators	Self-sufficiency of electric power sector Export dependency of electric power sector Import dependency of electric power sector

RES – renewable energy sources; OFF – organic fossil fuels.

The expected result of the research is the finding of the contradictions in the UA and EU electric power sector development, which must be overcome during the rebuilding of Ukraine's electric power sector after the war-time.

3. Results

3.1. Input-output models of electricity flows in Ukraine and EU

In this paper, the Sankey diagrams of electricity flows are depicted of Ukraine and the EU (figure 2, figure 3), which contain eight stages described below.

The first stage presents primary energy sources which were used for electric power generation

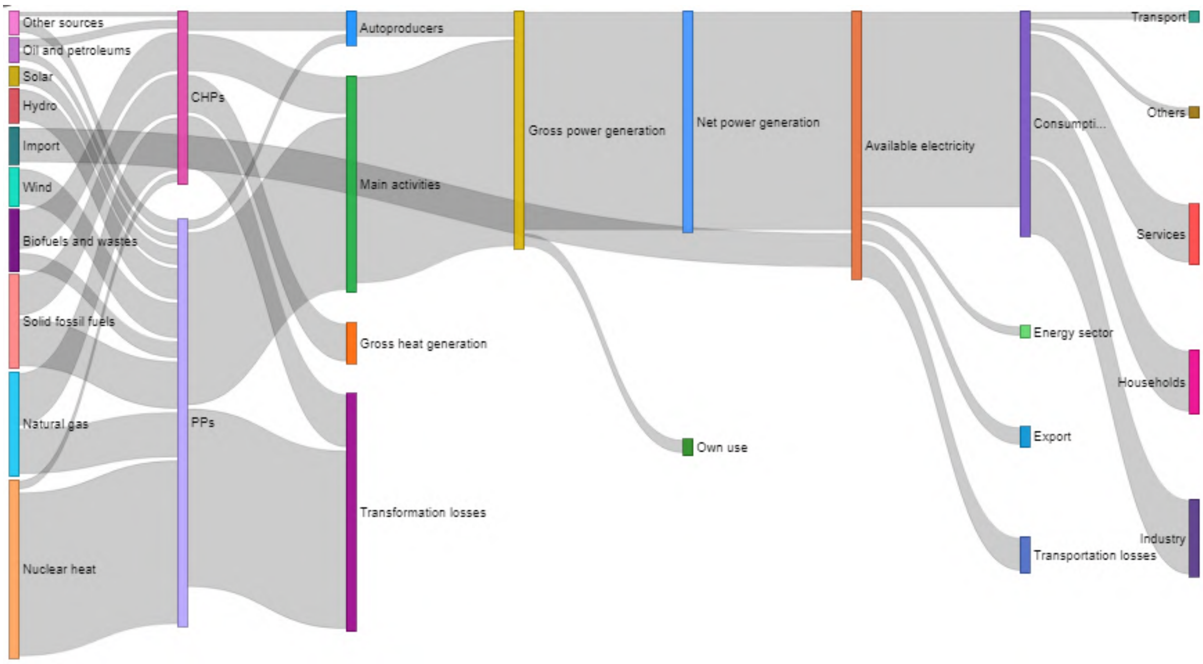

Figure 2. Sankey diagram of the EU electric power sector in 2020 (based on [20]).

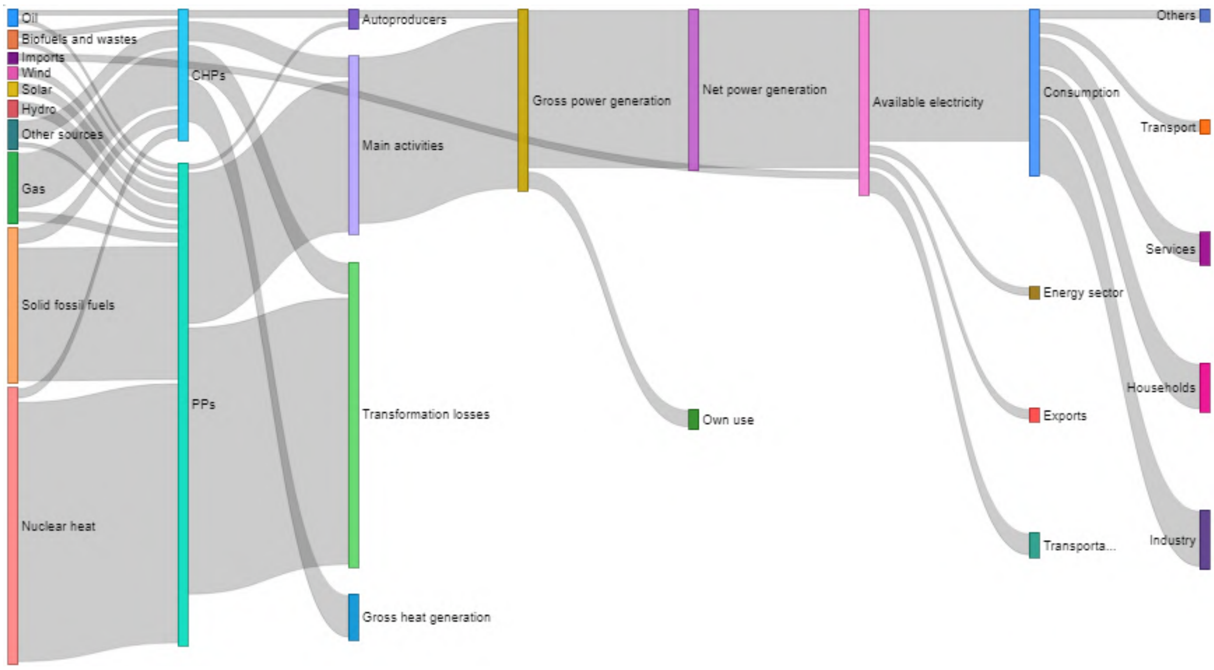

Figure 3. Sankey diagram of the UA electric power sector in 2020 (based on [20]).

(solid fossil fuels, nuclear heat, renewables etc.) and also the import of electricity as an external source of it. They are allocated between PPs and CHPs (the second stage). The third stage contains gross main and autoproducers' power generation, gross heat generation and transformation losses. In the fourth stage, the summarized gross output of power generation, which depends on the level of the state-of-the-art of used technologies. In the fifth stage, net power generation is presented as deducted sum from the gross output of electricity the own use of PPs and CHPs. The sum of net power generation and import of electricity gives the total available electricity for consumption (the sixth stage). But from the sum of available electricity is deducted electricity, which is exported, used for energy sectors and also volumes of distribution losses (the seventh stage). And in the eighth stage, final electricity consumption is allocated among final users: industrial and transport serctors, serives, households and others.

Comparison of electricity flows between stages of the the Sankey diagram allows to provinde qualitative assessment and determine contradictions of electric power sector development (table 2).

Table 2. Qualitative assessment of the EU electric power sector development (based on Sankey diagram analysis).

Indicator	EU				UA			
	1991	2000	2010	2020	1991	2000	2010	2020
Energy efficiency indicators								
Energy efficiency of transformation of electricity only	39	41	43	50	32	34	35	36
Energy efficiency of transformation of cogeneration	55	61	62	63	85	81	76	68
Energy efficiency of generation	94	95	95	96	94	93	92	92
Energy efficiency of transportation electricity	8	9	10	13	13	10	8	9
General energy efficiency of electric power sector	29	32	35	40	23	22	23	26
Structural indicators								
Share of RES in transformation inputs of electric power sector	6	8	13	25	1	2	3	4
Share of OFF in transformation inputs of electric power sector	58	52	49	38	72	51	49	40
Share of cogeneration in gross electricity generation	19	17	23	22	11	11	9	11
Share of autoproducers in transformation output of electricity generation	9	6	8	10	3	3	3	2
Share of commercial electricity consumption	49	46	39	39	75	61	56	45
Share of non-commercial electricity consumption	49	52	59	58	17	34	42	51
Security and Integration indicators								
Self-sufficiency of electric power sector	99	97	96	93	102	122	114	110
Export dependency of electric power sector	7	7	6	6	9	24	14	12
Import dependency of electric power sector	8	10	10	13	7	2	0	2

3.2. Mainstream trends of the EU electric power sector development

The EU strives to be a leader in implementing a climate-neutral policy. The main emphasis is dealt with electricity, which can be produced in a carbon-free way and will satisfy all the energy needs of each branch of society. For this purpose, appropriate transnational legislation, regional and national energy strategies are implemented. Consequently, significant structural shifts are taking place in the EU electric power sector in the direction of achieving the objective of carbon neutrality by 2050 [22]. Based on the Sankey diagram analysis, 6 mainstream trends in the EU electric power sector development can be admitted from 1991 to 2020.

Above all is *the decarbonization of the EU electric power sector*. Firstly, in 1991-2000, there was a shift towards nuclear energy and its share exceeded the share of power generation based on solid fossil fuels. In 2010-2020, the share of nuclear energy (considering the events at the Fukushima Daiichi in 2011) returned to the previous values of 34-35 %, while the share of power generation based on solid fossil fuels continued its decline.

Replacement of power generation based on solid fossil fuels also occurred due to the deployment of gas-fired electricity generation, and its share stabilized in 2010-2020 at the level of 19 %. The primary the deployment of gas-fired power generation was due to its higher energy efficiency and climate friendliness, but later it began to play the role of supporting RES-based power generation and only with the integration of national electricity markets, the requirements for the growth of gas-fired power generation went down. There was a permanent tendency to abandon oil-fired power generation based, down to 2 % in 2020.

The active deployment of unconventional RES-based power generation began in the 2000s starting with wind and biofuels. In 2020, the total share of all types of unconventional RES-based power generation reached 20 %, including 10 % based on biofuels and wastes and 10 % based on intermittent RES power generation (solar and wind). The share of hydropower generation will remain relatively stable, at the level of 5 %, aiming to secure the natural conditions of European water basins.

Thus, the structure of EU power generation accounted for 60 % of low-carbon energy sources in 2020. In absolute terms, the volumes of all types of fossil-fired power generation, except for gas, declined, while unconventional power generation grew rapidly.

With the first trend is strongly connected the second one, which is *deployment of highly efficient cogeneration*. In 1991-2000, there was an insignificant reduction in the share of cogeneration due to the abandonment of outdated cogeneration technologies based on solid fossil fuels. Recovery of cogeneration took place in 2000-2010, which occurred through the development of gas-fired cogeneration, and cogeneration based on biofuels and wastes. In 2010-2020, the share of cogeneration slightly decreased, as well as due to the growth of cogeneration based on biofuels and wastes, and the reduction of cogeneration based on solid fossil fuels.

There were also structural shifts towards an increase in the share of power generation in the structure of the gross output of cogeneration, on 40 % in absolute terms, while the share of heat generation, on the contrary, decreased on 10 % in absolute terms.

In general, the development of cogeneration is considered a way to reduce the useful losses of the electric power sector imposed by the technological limitations of mono-power generation technologies. Structural and technological changes made it possible to increase the energy efficiency of cogeneration from 55 % in 1991 to 63 % in 2020.

The third trend is *increasing the energy efficiency of the electric power sector at all stages*. In addition to increasing the energy efficiency of cogeneration, changes in the mono-power generation led to a reduction in transformation losses, which were down to 50 % in 2020. Firstly, this happened due to the deployment of intermittent RES-based power generation, the input and output energy flows of which are equated. Secondly, there was also an increase in the energy efficiency of gas-fired power generation up to 53 %, mainly due to the development of combined steam-gas cycles and the improvement of the working characteristics of gases. The fastest growth rates of energy efficiency were fixed for biofuel-based power generation up to 34 %, which was due to the advancements in biofuel preparation technologies.

At the same time technological and commercial limitations restricted changes in the energy efficiency of nuclear and solid fossil fuel power generation, which increased slightly.

Increasing the energy efficiency of power generation can be confirmed by the increasing net output from gross power generation. In 2020, the efficiency of electricity production increased by 2% compared to 1991. The most significant growth was achieved over the past 10 years, by 0.8 %, while over the previous 20 years this rate increased only by 1.1 %.

The useful electricity flows are also reduced by its losses in the grids, which in the EU nonetheless increased up to 13 % in 2020 (reasons for this originated from the 4th trend of the EU electric power sector development).

The above-mentioned led to the general energy efficiency increase of the EU electric power sector from 29 % in 1991 to 40 % in 2020.

Decentralization is the fourth and distinctive trend of the EU electric power sector. The causes of the growth of transportation electricity losses are straightly associated with increasing electricity flows through distribution grids, which a priori have larger losses against transmission ones. In absolute terms, distribution losses more than doubled in 1991–2020.

This trend can also be confirmed by the share of autoproducers in the total EU power generation. Their production increased by 28 % in absolute terms in 2020 against 1991. Reduction of autoproducer generation happened in 1991-2010 and associated with rapid declining mono-power generation, and was stopped only in 2010-2020 through the deployment of RES-based power generation. Compared to PP autoproducers, CHP autoproducers were continuously increasing the power generation. Their volumes increased in 2.7 times and in 4 % by share.

Thus, more and more EU electricity consumers aimed at being prosumers and self-providing their own electricity and heat needs. Surplus electricity is transmitted through the distribution network.

Opening the boundaries of the national electricity markets of the EU member states and increasing their electricity dependency form the fifth trend, that should be viewed in a comprehensive manner. The development of market trading, the deployment of RES-based power generation, and the desire to create a single market space on and beyond the EU initiated the growth of external electricity flows. Thus, the import and export of electricity increased more than double in 1991-2020. Subsequently, the self-sufficiency of the EU electric power sector decreased to 93 %, import dependency increased to 13 %, while export dependency remained approximately the same in 2020. So, the EU electric power sector goals caused the need for redistribution of electricity surpluses and shortcomings of national electric power systems.

Awareness of the value of electricity in modern society forms sixth trend – *its penetration in all spheres of economy.* EU final electricity consumption increased by 26 % in absolute terms from 1991 to 2020. There had been made significant structural shifts in the final electricity consumption structure. Firstly, these shifts were associated with responsible electricity consumption by industry. The plateau of industrial electricity consumption was reached in 2000-2010, while it decreased in 2010-2020, returning almost to the level of 1991 in 2020. Therefore, the share of industrial electricity consumption decreased from 45 % in 1991 to 37 % in 2020. At the same time, the improvement of the quality of life led to increasing electricity consumption by the services and households, the volumes of which increased by 1.7 times and 1.4 times respectively in 1991-2020. Therefore, it can be admitted the ongoing convergence of the shares of the three types of activity in the EU: industry, services, and households.

3.3. Key tendencies of the UA electric power sector development

The European course of the national policy of Ukraine has been consistently implemented in the energy sector since 2010, as a member of the Energy Community. However, the implementation of the European energy policy in Ukraine requires significant changes in electric power sector through its reconstruction, modernization and integration into the European energy space. Ukraine strives to catch up with European development trends and achieve carbon neutrality by 2060. The key trends in the UA electric power sector compared with EU ones can be defined as follows.

Compared to the EU the first one Ukrainian trend can be stated as *gas-to-coal switching of the electric power sector of Ukraine.* The UA power generation decreased by 49 % in 1991-2020 as a request of decreasing electricity demand. In the structure of transformation inputs for power generation, a significant increase in the share of solid organic fuel happened in the 2010s down to 36 %. The share of gas-fired power generation, after a slight increase in 1991-2000, gradually decreased after 2000 to 11-12 % in 2010-2020 aiming to decline the gas dependency of Ukraine. The share of nuclear heat in power generation has been constantly growing from up to 53 % in 2020, but in absolute terms it remained approximately the same, having increased only by 3.5 %.

The share of other energy sources increased only by 1 for hydro-, bio-, solar and wind generation. In absolute terms, solar power increased by 513 times, and wind power by 62 times, while hydropower and bioenergy decreased by 42 % and 35 % respectively, in 2010-2020. Oil-fired power generation declined to almost zero in 2020.

Therefore, Ukraine is forced to abandon the more climate-friendly gas-fired power generation, and support dirty power generation based on solid fossil fuels at a sufficient level, and limit hydropower generation for the deployment of RES power generation. This phenomenon nowadays is known as the green-coal paradox.

In contradiction to the EU, the second Ukrainian trend is *reducing the volumes and energy efficiency of cogeneration.* Power generation by cogeneration decreased by 47 % from 1991 to 2020 and was accompanied by a 37 % decrease in heat generation due to the lack of sufficient heat demand in the CHPs-related territories. Despite this, the share of transformation inputs for cogeneration increased from 12 % in 1991 to 17 % in 2020, while the share of cogeneration in gross electricity generation remained unchanged at the level of 11 %.

Thus, the energy efficiency of cogeneration decreased to 68 % in 2020 and was associated with a decrease in the heat share in gross output, and the physical obsolescence of cogeneration.

Significant shifts considered in the structure of cogeneration, gas-fired cogeneration decreased to 45 % by the share, and 51 % in absolute terms in 2020. The share of coal-fired cogeneration, on the contrary, increased to 10 %. The share of nuclear cogeneration remained significant and unchanged at the level of 5 %. Noteworthy the share of other energy sources for cogeneration increased to 12 % in 1991-2020, which meant a significant unclassified part of cogeneration.

Stable too low energy efficiency alienates the Ukrainian electric power sector from the European common one. Transformation losses of the mono-power generation underwent an insignificant reduction from 68 % to 64 % in 1991-2020. So, the energy efficiency of mono-power generation increased only from 32 % to 36 %. This was largely made by the deployment of RES-based power generation, as well as the reconstruction of several coal-fired steam turbine power units with their transfer to the technology of supercritical parameters. Thus, the efficiency of power generation in the coal-fired power industry increased from 30 % in 1991 to 33 % in 2020.

The Ukrainian power generation is physically and morally obsolete, which also leads to significant electricity for the own use of power plants. Through the time the energy efficiency of power generation declined from 94 % in 1991 to 92 % in 2020.

The physical outdated and lack of modernization of power networks also led to high electricity losses through its transmission and distribution. However, the share of electricity losses steadily decreased from 13 % to 9 % in 1991-2020 (as in the EU case, the cause can be found in the next trend).

In general, the energy efficiency of the UA electric power sector accounted for 26 % in 2020, increased only by 3 % compared to 1991.

Centralization is the fourth key trend of the UA electric power sector development, distinct from the EU. Electric power sector of Ukraine is a Soviet heritage of a centralized type. Since the independency of Ukraine, only transmission networks have undergone upgrades to synchronize with ENTSO-E, while distribution networks remain obsolete. This fact is associated with a decrease in transport losses of electricity.

The deindustrialization of Ukraine has led to a greater centralization of the electric power sector by the closure of a number of autoproducers of electricity. Their share in the structure of gross output decreased by 65 % in absolute terms, incl. CHP autoproducers by 62 % and PP autoproducers by 74 % in 1991-2020.

Isolation and self-sufficiency of the UA electric power sector can be recognized as fifth trend. Ukraine's electric power sector has been and remains self-sufficient, the net power generation has always exceeded consumer needs. In 1991 this level was at 102 %. There was its growth to 122 % in the 2000 and Ukraine actively traded electricity with the CIS countries. The part of the Ukrainian electric power system was synchronized with ENTSO-E since 2002. This led to the opening of electricity exports to Europe. Electricity trading with the CIS countries was close to zero level in the 2010s and there were only technical electricity flows. The opening of electricity imports from Europe to Ukraine became possible after the implementation of the European electricity market model in Ukraine in mid-2019. In 2020, the import dependency of the Ukrainian electric power sector was at 2 %, while the export dependency was at 12 %.

Currently, Ukraine has limited opportunities for electricity trading with neighbouring countries, which are limited by cross-border transmission and inconsistencies with European trading rules, even despite the full synchronization of the Ukrainian energy system with the European common one.

Deindustrialization of the UA alters electricity consumption patterns and is the sixth trend. It can be admitted similar structural shifts in Ukrainian final electricity consumption compared to the EU, but the reasons of these are great differ. Final electricity consumption in Ukraine decreased by 43 % in 1991-2020. At the same time, a similar drop was already fixed in 1991-2000, which was stopped in 2000-2010, reaching an 18 % increase in electricity consumption in 2010. However, the occupation of part of the territories and the economic potential of Ukraine decreased the final electricity consumption by 15 % in 2020 against 2010.

The falling industrial production led to a reduction in industrial electricity consumption by 76 % in 1991-2020, although there was an increase of 9 % in 2000-2010, and a decrease of 31 % in 2010-2020. Consequently, the share of industrial electricity consumption in Ukraine has decreased from 68 % in 1991 to up to 40 % in 2020. The declining industrial activity led to a reduction in transport flows.

Electricity consumption by the service sector, on the contrary, decreased only by 38 % in 1991-2000, while their volumes increased by 144 % in 2000-2020, led to an increase in its share to 19 % in 2020. Notwithstanding the socio-economic conditions, household electricity consumption increased all time in 1991-2020. And even the loss and occupation of part of the territories of Ukraine led to a reduction in household electricity consumption only by 0.5 % in 2020 compared to 2010. The share of household electricity consumption reached 32 % in 2020.

Consequently, in 2020, the total share of non-commercial electricity consumption exceeded the share of commercial electricity consumption by 6 %, although in 1991 this ratio was reversed exceeded 4 times, in 2000 – 2 times, and in 2010 – 14 times.

4. Discussion and conclusions

It is difficult to overestimate the role of the electric power sector in ensuring the energy transition to sustainable energy in the future. In each country, the electricity sector is unique, which depends on the specific technical conditions of the electric power system, the climate and natural conditions of the related territory, and government regulation of electricity market. But there is a common vision of the future, and it is possible to highlight the general trends and characterize individual transformation processes on the path of sustainable development. This study proposes methodological support for the analysis of the electric power sector development, which includes the following.

- Input-output model of electricity flows, which considers different stages of the electric power chain starting from primary energy sources and ending with electricity consumption by types of activity;
- Sankey diagram analysis of electricity flows in MS Power BI software that allows slicing data for time periods and countries.
- Qualitative assessment of electric power sector development, which is provided by three group indicators such as energy efficiency, structural, and security and integration.

Ukraine aims to be a full member of single European community and comply with the European framework of economic policy, including the energy sphere. But there is still a significant gap between Ukraine and European member-states. By comparing the UA and EU trends of electric power sector development it was possible to determine the contradictions of the Ukrainian one with the general vision of the EU. Understanding of these contradictions is a background for solving them and making comprehensive decisions for rebuilding electric power sector after the war-time. Among them are the following.

- The first one is that Ukraine is forced to keep coal-fired generation for demoting gas dependency and as for supporting RES-generation. At the same time the EU prioritizes the development of ecology-friendly generation, both gas and renewable, looking for more favourable market conditions to meet primary energy source needs.
- The second one is the falling of cogeneration in Ukraine while as the EU strives to support deployment of highly-efficiency cogeneration. But the solution to this issue in Ukraine depends on the comprehensive development of electric power and district heating sectors.
- The third one is outdated and low energy efficient electric power generation in Ukraine, while in European countries development of highly efficient generation supporting through capacity remuneration mechanisms or even green auctions. In Ukraine, such mechanisms aren't implemented yet.
- The fourth trend is the centralization of the UA electric power sector vs the decentralization of the EU one. Ukrainian electricity consumers have restricted investment abilities and legal obstacles in deploying their own generation, while the EU strives to support the development of distributed generation.
- The fifth one is differentiation on energy security: whereas the EU aims at create single European electricity market, disregarding electricity dependency of member-states, Ukraine remains isolated but self-sufficient due to the lack of cross-border capacities. Synchronization of the Ukrainian electricity system with the European one poses new challenges for Ukraine: where and how to integrate into the European space.
- And the last but not least trend is divergence in the electricity consumption patterns in Ukraine and the EU. Unfortunately, it cannot be solve internally inside the electric power sector and it has to adopt to these challenges: through the develop more flexible capacities, provide incentives for consumers of levelling the electricity consumption schedule.

The general conclusion of this research is following: although Ukraine strives to adhere to European trends of the deployment of RES-based electric power generation, however, other trends were contradictory, intensive shifts were insignificant and were complicated by the physical and moral obsolescence of electric power system.

As can be seen, the solution of of the most of contradictions greatly depends on the public authority actions and should be included in the national energy policy of Ukraine. It can be supposed that these contradictions will be exacerbated after the war-time but the synchronization of Ukraine with the ENTSO-E is the great challenge but also the window of opportunities. Thus, government decisions have to be made for the rebuilding of electric power sector.

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References

[1] Chen Q, Balian A, Kyzym M, Salashenko T, Gryshova I and Khaustova V 2021 *Sustainability* **13**(22) 12343 URL https://doi.org/10.3390/su132212343
[2] Zanuda A 2023 How was it possible to restore the light after Russia's destruction of Ukraine's energy sector and whether it will last bBC News Ukraine URL https://www.bbc.com/ukrainian/features-64820897
[3] ten Raa T 2009 *Input-output economics: Theory and applications: Featuring Asian Economies* (World Scientific) URL https://doi.org/10.1142/6968
[4] IEA 2021 World Energy Outlook 2021 Tech. rep. International Energy Agency Paris URL https://www.iea.org/reports/world-energy-outlook-2021
[5] Chong C, Zhang X, Kong G, Ma L, Li Z, Ni W and Yu E H C 2021 *Sustainability* **13**(21) 12239 URL https://doi.org/10.3390/su132112239
[6] Leontief W W 1936 *The review of economic statistics* 105–125 URL https://doi.org/10.2307/1927837
[7] United States Department of State 1949 *Energy Resources of the World* (U.S. Government Printing Office) URL https://books.google.com.ua/books?id=uRRRxQEACAAJ&printsec=frontcover&redir_esc=y#v=onepage&q&f=false
[8] Schmidt M 2008 *Journal of industrial ecology* **12**(2) 173–185 URL https://doi.org/10.1111/j.1530-9290.2008.00015.x
[9] Ma L, Chong C, Zhang X, Liu P, Li W, Li Z and Ni W 2018 *Sustainability* **10**(2) 344 URL https://doi.org/10.3390/su10020344
[10] Chong C, Ma L, Li Z, Geng J and Zhang T 2014 A programmed data-processing method for mapping energy allocation sankey diagram of china *Proceedings of the International Conference on Power and Energy, Shanghai, China* pp 29–30 URL https://doi.org/10.1201/b18409-43
[11] de Córdoba G F and Molinari B 2022 *Heliyon* **8**(9) e10717 URL https://doi.org/10.1016/j.heliyon.2022.e10717
[12] Cuba N 2015 *Landscape and Urban Planning* **139** 163–167 URL https://doi.org/10.1016/j.landurbplan.2015.03.010
[13] Otto E, Culakova E, Meng S, Zhang Z, Xu H, Mohile S and Flannery M A 2022 *Journal of Geriatric Oncology* URL https://doi.org/10.1016/j.jgo.2021.12.017
[14] Soundararajan K, Ho H K and Su B 2014 *Applied energy* **136** 1035–1042 URL https://doi.org/10.1016/j.apenergy.2014.08.070
[15] Subramanyam V, Paramshivan D, Kumar A and Mondal M A H 2015 *Energy Conversion and Management* **91** 342–352 URL https://doi.org/10.1016/j.enconman.2014.12.024
[16] Ouyang J, Mativenga P, Liu Z, Goffin N, Jones L, Woolley E and Li L 2022 *Energy* **243** 123069 URL https://doi.org/10.1016/j.energy.2021.123069
[17] Wang D, Gryshova I, Balian A, Kyzym M, Salashenko T, Khaustova V and Davidyuk O 2022 *Sustainability* **14**(4) 2236 URL https://doi.org/10.3390/su14042236
[18] Eurostat 2021 Energy balance flow for European Union (27 countries) 2021 URL https://ec.europa.eu/eurostat/cache/sankey/energy/sankey.html
[19] Microsoft 2022 Power BI URL https://app.powerbi.com/
[20] Eurostat 2023 Database - Energy URL https://ec.europa.eu/eurostat/web/energy/database

[21] European Parliament, Council of the European Union 2008 *Official Journal of the European Union* **L 304** 1–62 URL http://data.europa.eu/eli/reg/2008/1099/oj
[22] UNFCCC 2023 National Determined Contributions Registry URL https://unfccc.int/NDCREG

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Fuzzy logic in the decision-making tasks of connecting renewable energy sources into the electricity supply system

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Fuzzy logic in the decision-making tasks of connecting renewable energy sources into the electricity supply system

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Abstract. The Third and Fourth EU Energy Packages, as well as the Energy Strategy of Ukraine "Safety, Energy Efficiency, Competitiveness" until 2035, define the development of electricity production using renewable energy sources among the priorities of the energy sector. In this situation, the decision-making process on the integration of renewable energy sources into the electricity supply system is of particular importance. The article develops a fuzzy model for assessing the risks of connecting (integration) renewable energy sources to the power supply system. The toolkit, based on logical rules, allows modeling various connection options. The data obtained can then be used to set requirements for the parameters of the electrical installation at the stage of issuing technical specifications to the customer. The modeling results demonstrate the adequacy of the developed knowledge base and the possibility of using it to develop a methodology for the controlled and efficient connection of renewable energy sources to the power grid.

1. Introduction

In the past, national energy planning involved the development of a centralized infrastructure investment program for a certain period of time. However, in the current geopolitical context, environmental damage, depletion of fossil fuels and territorial imbalances are factors that require a change in the energy mix, and the introduction of measures to invest in energy diversification and the integration of renewable energy sources (RES).

At present, the construction of clean energy generation facilities is carried out solely from the standpoint of commercial attractiveness, but not from the standpoint of the country's economic development, environmental friendliness and consumer interests. The rapid development of green energy is taking part without consideration of the real needs of Ukraine's energy system for additional generating capacity. This can lead to destabilization of its functioning and the possibility of emergencies.

Decision-making on the integration of RES into the electricity supply system should be based on an analysis of the modes and processes that arise under different options for connecting RES. However, decision-making will almost always take place in conditions of incomplete information, which will cause some uncertainty about the results of these connections. In such circumstances, the use of fuzzy logic elements in the process of assessing risk factors is justified.

2. Purpose and objectives

The purpose of the article is to develop a methodology that allows for a controlled and efficient connection of RES to power grids based on a risk profile. The objective of the article is a study of the use of fuzzy logic for risk assessment in the connection of RES to the electricity supply system, namely, a comprehensive consideration of the influence of factors.

3. Research material and results

According to a report by the International Renewable Energy Agency (IRENA), 3064 GW of renewable generation capacity was in operation worldwide at the end of 2021 [1]. Of this volume, 40% is accounted for by hydroelectric power plants, 28% by solar power plants and 27% by wind power plants. However, solar and wind power have dominated the expansion of renewable energy capacities lately (figure 1).

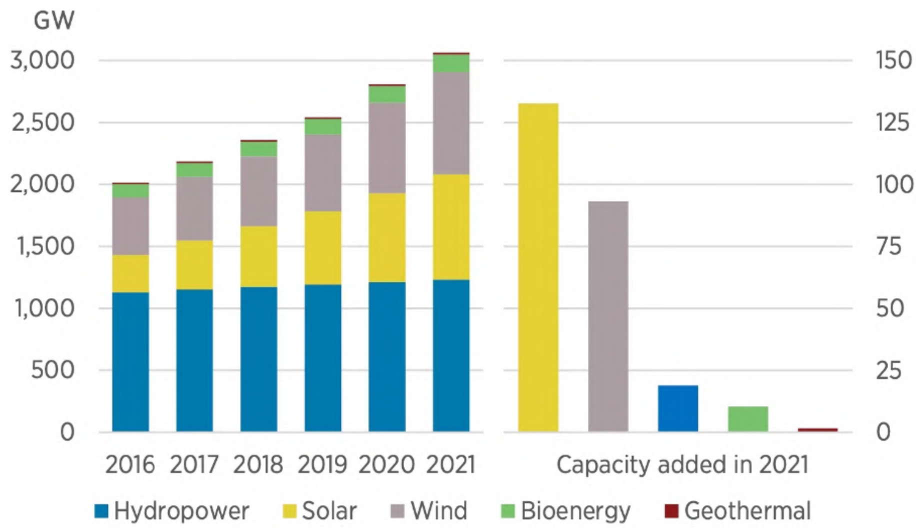


Figure 1. Growth of RES capacities [2].

The studies [3, 4] has shown that further development towards increasing the share of solar and wind power plants in the generation of the power system poses significant challenges to ensuring reliable electricity supply and efficient management of the distribution system. In view of this, as well as the growing technical capabilities of RES and related equipment, there is a need to set requirements for the main equipment or to install additional equipment for flexible and dynamic regulation of RES operation.

Unfortunately, there is currently no effective, comprehensive system for assessing and managing risks in the integration of RES into the electricity supply system. The practical aspects of risk management in this segment have not been sufficiently researched and covered, considering the experience of the world's leading countries and the grid specifics of the electricity supply system. There is an urgent need to create a comprehensive risk management system for the integration of RES, which will be adapted to the current realities of the Ukrainian power system.

In the energy sector, decision-making often takes place with significant incomplete information, lack of statistical estimates, and in poorly formalized conditions. In these circumstances, many researchers suggest using fuzzy logic for decision-making.

Courtecuisse et al [5] use this method because it facilitates the analysis and definition of fuzzy control algorithms adapted for complex hybrid systems. In addition, the fuzzy logic method is adapted to solve the problems of forecasting energy production from RES and changes in grid frequency with load changes. This allows them to avoid accurate and detailed models of different sources and system topology.

Dimitroulis and Alamaniotis [6] presents a fuzzy logic-based energy management system for residential prosumers, who produce electricity for their own consumption and sell it to the grid. The use of a mathematical model based on fuzzy logic allows reducing energy consumption costs and increasing profits from the sale of excess energy to the grid. This was confirmed by the results of practical implementation.

The article [7] addresses the problem of optimal control of energy storage systems to maintain voltage/frequency in distribution power grids, considering the degradation of batteries. Liu et al propose an optimal fuzzy control method that maximizes the useful effect, reduces power losses, and minimizes battery degradation.

Yahyaoui et al [8] proposes and evaluates a methodology based on fuzzy logic for energy management in autonomous installations with photovoltaic panels and limited battery capacity. The decision-making process includes consideration of the system's autonomy, battery protection against deep discharge and overcharge, and power supply stability.

Ziemba [9] also use a fuzzy logic model, and more exactly, a modified fuzzy TOPSIS method for multi-criteria assessment of investments in onshore wind farms in Poland. This method is also used to determine the most cost-effective investment. The fuzzy TOPSIS method allows capturing the uncertainty of input data as well as conflicting criteria.

Pankovits et al [10] uses fuzzy logic algorithms to integrate renewable energy generation and storage units, using the example of a railway substation. This made it possible to contribute to limiting the excess of the estimated capacity from the grid and to promote local consumption of renewable energy through empirical supervision parameters. The multi-criteria approach, including energy, environmental and economic constraints, was implemented at different time levels.

De Carvalho et al [11] presented a methodology using fuzzy logic to optimize the control of an embedded power system. The system under consideration was equipped with a supercapacitor energy storage device that performs the function of power smoothing and peak reduction. The optimization goals were to minimize the voltage fluctuations of the DC circuit and to improve the system efficiency by reducing power dissipation.

In turn, Baqui [12] formulated an automated decision-making model for the allocation of power grid resources using fuzzy logic algorithms. The rule base was created on the knowledge of the subject area and analysis of the operator's decision-making activities.

The article of Ibrahim et al [13] is devoted to the development of a fuzzy logic-based energy management system for hybrid energy sources. The proposed system uses fuzzy logic to make decisions on load distribution between different energy sources depending on external conditions and consumer requirements. In addition, the system can adapt to changing operating conditions and ensures optimal energy utilization. Studies have shown that the proposed fuzzy logic-based electricity consumption management system is effective and can reduce electricity costs.

Castillo-Calzadilla et al [14] describes a methodology for assessing positive energy districts (PEDs) based on fuzzy logic. A PED is an area where most of the energy consumed is provided by renewable sources and excess energy is transferred to the grid. The use of this methodology can help determine the degree of sustainable development and energy security in different PEDs. The results of the study demonstrate the effectiveness of the proposed methodology and the possibility of its use to assess positive energy districts in different regions and cities.

Fuzzy logic has also been used to evaluate crops that can be grown profitably for bioenergy production. Lewis et al [15] used a fuzzy spatial suitability model with physical and economic variables to identify non-agricultural areas that could be profitably cultivated with bioenergy crops that are more resilient to environmental conditions.

Alekhya et al [16] consider risk assessment using fuzzy logic. This study proposes a risk assessment methodology that uses fuzzy logic to model and analyze uncertainty. This methodology involves creating a mathematical model that includes a set of factors and fuzzy rules to assess the degree of influence of each factor on the project cost. The use of fuzzy logic allows modeling uncertainty and ambiguity in risk assessment. The results of the study demonstrate the effectiveness of the proposed methodology and its ability to more accurately assess the risks of project cost overruns.

In the tasks of risk assessment when connecting RES and decision-making under uncertainty, problems arise that are difficult to solve using traditional methods. In a real-world model, there is always a technological scatter of parameters due to the complexity of the system. To solve this problem, it is necessary to use fuzzy concepts and knowledge that describe the control process using productive if-then rules. The most important advantages of this method of evaluation include the ability to use the expert's experience without drawing up differential equations. The use of fuzzy logic for decision-making is most useful for systems with poorly formalized processes [17].

The advantages of using a fuzzy logic model in decision-making are as follows:

- fuzzy logic methods make it possible to describe risk factors in a qualitative, verbal way by introducing the concepts of linguistic variables, the meaning of which is understandable to the expert;
- the use of fuzzy sets allows formalizing more flexible relationships between the factors of each of the risks under study. This is more in accordance with the nature of the real interactions studied in the electric power industry;
- fuzzy methods make it possible to make decisions under conditions of incomplete information by synthesizing and analyzing qualitative values. This is important for decision-making in connecting RES to the power supply system.

In general, the mechanism of logical inference includes four stages [18]: introduction of fuzziness (fuzzification), fuzzy conclusion, composition and reduction to clarity, or defuzzification (figure 2). Fuzzy inference algorithms mainly differ in the type of rules used, logical operations, and the type of defuzzification method.

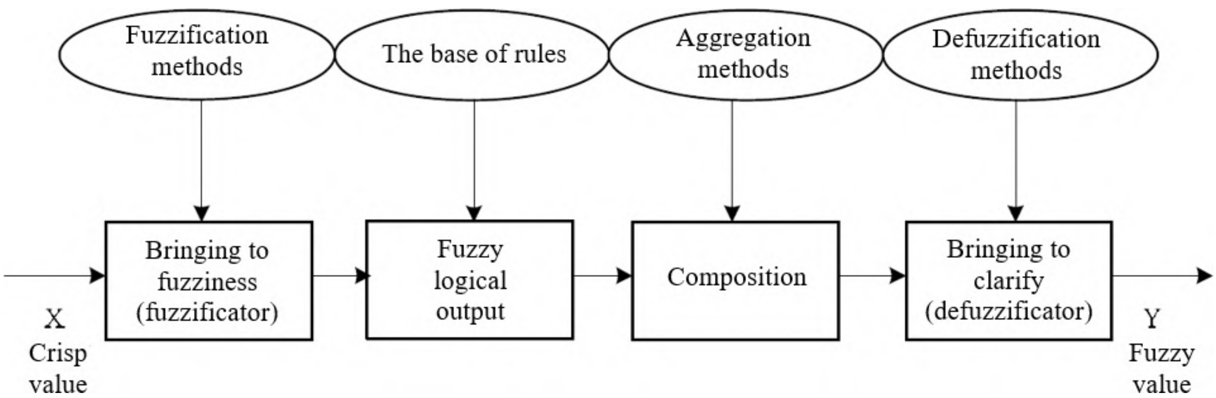


Figure 2. System of the fuzzy logic model.

Despite the complexity of the mathematical apparatus embedded in the algorithms, this approach allows for a fairly flexible model that will operate with numerous input arguments and provide a resultant value. The resulting value can be considered objective with a certain degree of approximation. Because there are a variety of subjective things, such as the assessment of specific threats by experts [19].

The Mamdani algorithm was used to create a risk profile for the integration of RES into the power supply system. The application of this algorithm allows us to qualitatively describe the possible causes (processes or phenomena) that contribute to the connection problem. Subsequently, with this information about the factors, it is possible to build a functional correspondence.

In Mamdani's model, each rule has a degree of execution ω_i, which is calculated as follows:

$$\omega_i(x_1, ...x_{n_x}) = \bigwedge_{j=1}^{n_x} \mu_{j,i}(x_j),\ i = 1...n_r, \tag{1}$$

where $\wedge$ – a fuzzy conjunction operation that corresponds to the "AND" operator in the rules; n_x – number of inputs; $\mu_{j,i}(x_j)$ – the membership function on the j-th input in the antecedent of the i-th rule; n_r – number of rules.

After the degrees of rule fulfillment are calculated, the fuzzy values of the rule constituents are calculated using implication (in Mamdani systems, the minimum operation is usually used).

Then, using the aggregation operation (in Mamdani systems, the maximum operation is usually used), the fuzzy output value with the membership function $\mu_{Yout}(y)$ is calculated according to the expression:

$$\mu_{Yout}(y) = \bigvee_{i=1}^{n_r} (\omega_i(x_1, ...x_{n_x}) \wedge \mu_{Yi}(y)), \tag{2}$$

where $\vee$ is an aggregation operation that corresponds to the union of fuzzy rules by ELSE, which is equivalent to a disjunction in the Mamdani system; $\wedge$ – implication operation (equivalent to a conjunction in the Mamdani system); $\mu_{Yi}(y)$ - is the membership function of the concatenation of the i-th rule.

After the rule inputs have been processed by the algorithm described above and the fuzzy output $\mu_{Yout}(y)$ is obtained, it is necessary to find the corresponding crisp value using defuzzification y^*. The main methods of defuzzification are the center of gravity, center of sums, and average maximum methods.

4. Practical application

The Matlab environment used in the study is a specialized package Fuzzy Logic Toolbox [20]. It is used to create and further use a fuzzy logic system in an interactive mode.

To assess the risks of integrating RES into the power supply system, indicators reflecting the impact of these sources on the system are used. These elements include such factors as: the occurrence of higher harmonics (Ku), voltage deviation from Un (ΔU) and reactive power flow ($\cos\varphi$). The occurrence of higher harmonics was defined by an ordered term set of values consisting of three terms: "low", "medium" and "high". The terms are listed in order from the most negative to the most positive. According to the tasks set, it is enough to select 3 linguistic variables to describe the aspects of the factor for further application of the fuzzy logic method. This scale is also used for other indicators (table 1).

Table 1. Scale for assessing linguistic variables.

Factors	Range	Scale (L) (M) (H) in rel. units		
Higher harmonics	0 % ...10%	0.90 ...0.94	0.92 ...0.98	0.96 ...1.0
Voltage deviation from Un	196 V ...264 V	0.85 ...0.91	0.88 ...0.97	0.94 ...1.0
Reactive power flow	0.75 ...1.0	0.75 ...0.85	0.80 ...0.95	0.90 ...1.0

A distinctive principle of the Mamdani method is that its rules of logical inference contain fuzzy values (membership functions) in their concretions (on the right side). The Matlab module includes 11 built-in membership types. However, in practice, it is convenient to use those membership functions that allow an analytical representation in the form of some simple mathematical function. This simplifies not only the corresponding numerical calculations, but also reduces the computational resources required to store individual values of these membership functions [21]. Therefore, in our study, we considered the triangular, trapezoidal, and simple Gaussian membership functions.

The triangular membership function (figure 3) is formed using a piecewise linear approximation.

A triangular function (for example, for the "medium" term of ΔU) can be given analytically

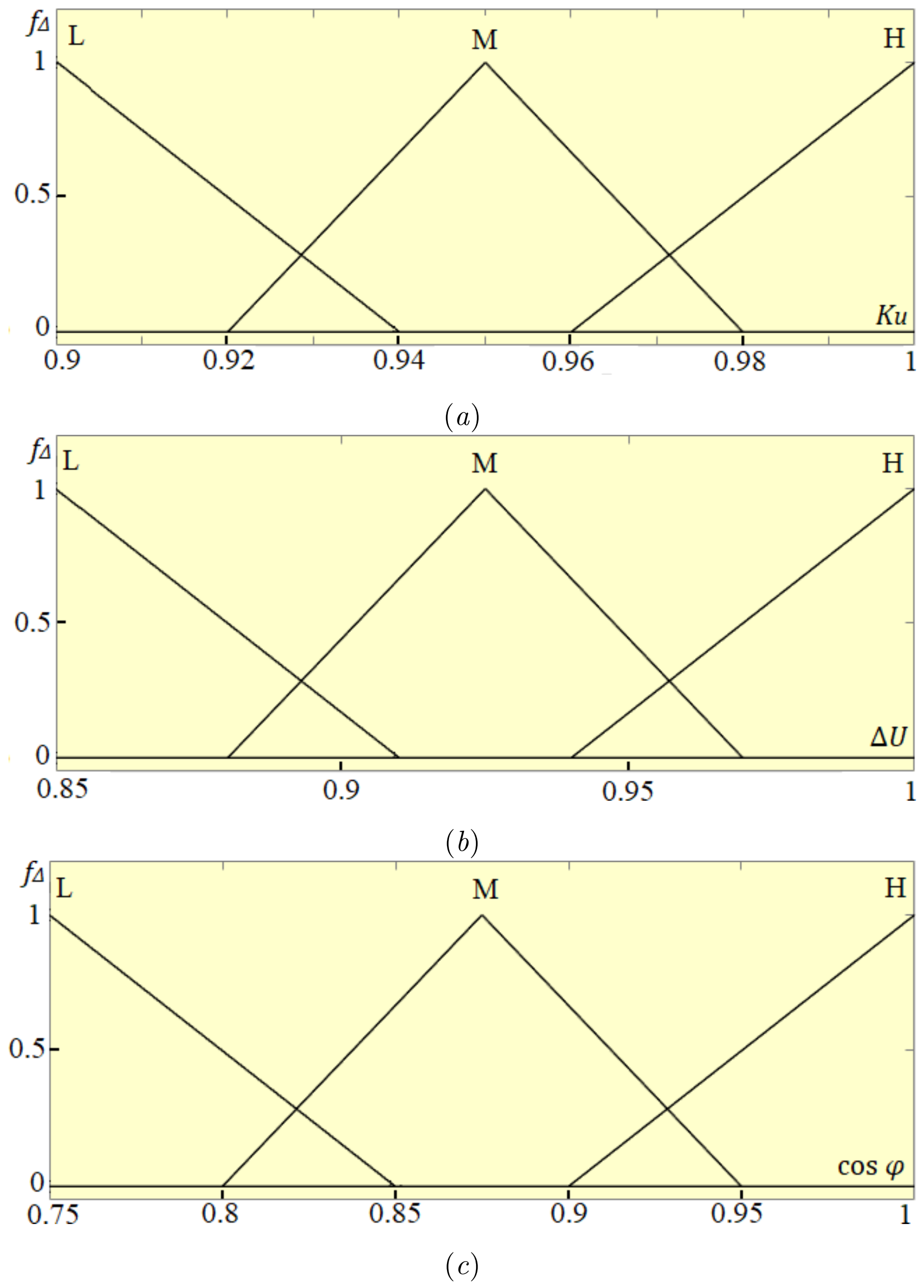


Figure 3. Graphs of the triangular membership function for variables $Ku(a)$, $\Delta U(b)$, $\cos\varphi(c)$.

by the following expression:

$$f_{\Delta}(\Delta U_m; a, b, c) = \left\{ \begin{array}{cc} 0, & \Delta U_m \leqslant a \\ \dfrac{\Delta U_m - a}{b - a}, & a \leqslant \Delta U_m \leqslant b \\ \dfrac{c - \Delta U_m}{c - b}, & b \leqslant \Delta U_m \leqslant c \\ 0, & c \leqslant \Delta U_m \end{array} \right\} =$$

$$= \left\{ \begin{array}{cc} 0, & \Delta U_m \leqslant 0.88 \\ \dfrac{\Delta U_m - 0.88}{0.925 - 0.88}, & 0.88 \leqslant \Delta U_m \leqslant 0.925 \\ \dfrac{0.97 - \Delta U_m}{0.97 - 0.925}, & 0.925 \leqslant \Delta U_m \leqslant 0.97 \\ 0, & 0.97 \leqslant \Delta U_m \end{array} \right\}.$$

The parameters a and c characterize the base of the triangle, and the parameter b characterizes its vertex. As you can see, this membership function generates a normal convex unimodal fuzzy set with a carrier – the interval (a,c), the boundaries $(a, c) \setminus \{b\}$, the kernel b and the mode b.

The following is a trapezoidal membership function (figure 4).

In turn, the trapezoidal (also for the term "medium" of ΔU) can be given analytically by the following expression:

$$f_T(\Delta U_m; a, b, c, d) = \left\{ \begin{array}{cc} 0, & \Delta U_m \leqslant a \\ \dfrac{\Delta U_m - a}{b - a}, & a \leqslant \Delta U_m \leqslant b \\ 1, & b \leqslant \Delta U_m \leqslant c \\ \dfrac{d - \Delta U_m}{d - c}, & c \leqslant \Delta U_m \leqslant d \\ 0, & d \leqslant \Delta U_m \end{array} \right\} = \left\{ \begin{array}{cc} 0, & \Delta U_m \leqslant 0.88 \\ \dfrac{\Delta U_m - 0.88}{0.91 - 0.88}, & 0.88 \leqslant \Delta U_m \leqslant 0.91 \\ 1, & 0.91 \leqslant \Delta U_m \leqslant 0.94 \\ \dfrac{0.97 - \Delta U_m}{0.97 - 0.94}, & 0.94 \leqslant \Delta U_m \leqslant 0.97 \\ 0, & 0.97 \leqslant \Delta U_m \end{array} \right\}.$$

The parameters a and d characterize the lower base of the trapezoid, and the parameters b and c characterize the upper base of the trapezoid. In this case, this membership function generates a normal convex fuzzy set with a carrier – the interval $(a,\ d)$, the boundaries $(a, b) \cup (c, d))$ and the kernel $[b,c]$.

A commonly used method of generating a membership function is to apply a Gaussian curve. Based on the Gaussian distribution function, two types of membership functions can be constructed: a simple Gaussian membership function (figure 5) and a bilateral one formed using different Gaussian distribution functions.

The symmetric Gaussian function for the "medium" term of ΔU is given analytically by the following expression:

$$f_G(\Delta U_m; \sigma, c) = e^{\dfrac{-(\Delta U_m - c)^2}{2\sigma^2}} = e^{\dfrac{-(\Delta U_m - 0.925)^2}{2 \cdot (0.015)^2}}.$$

In this expression, c is the coordinate of the maximum of the membership function; and σ is the concentration coefficient of the membership function.

The accuracy of risk assessment in the integration of RES depends on the completeness of the knowledge base. The flexibility of the analysis process is achieved by setting key decision-making rules. The course of logical inference is formed at the stage of defuzzification, in our case, using expert data obtained in the study [3]. For each rule, the membership functions of the input variables and the output variable are displayed (figure 6).

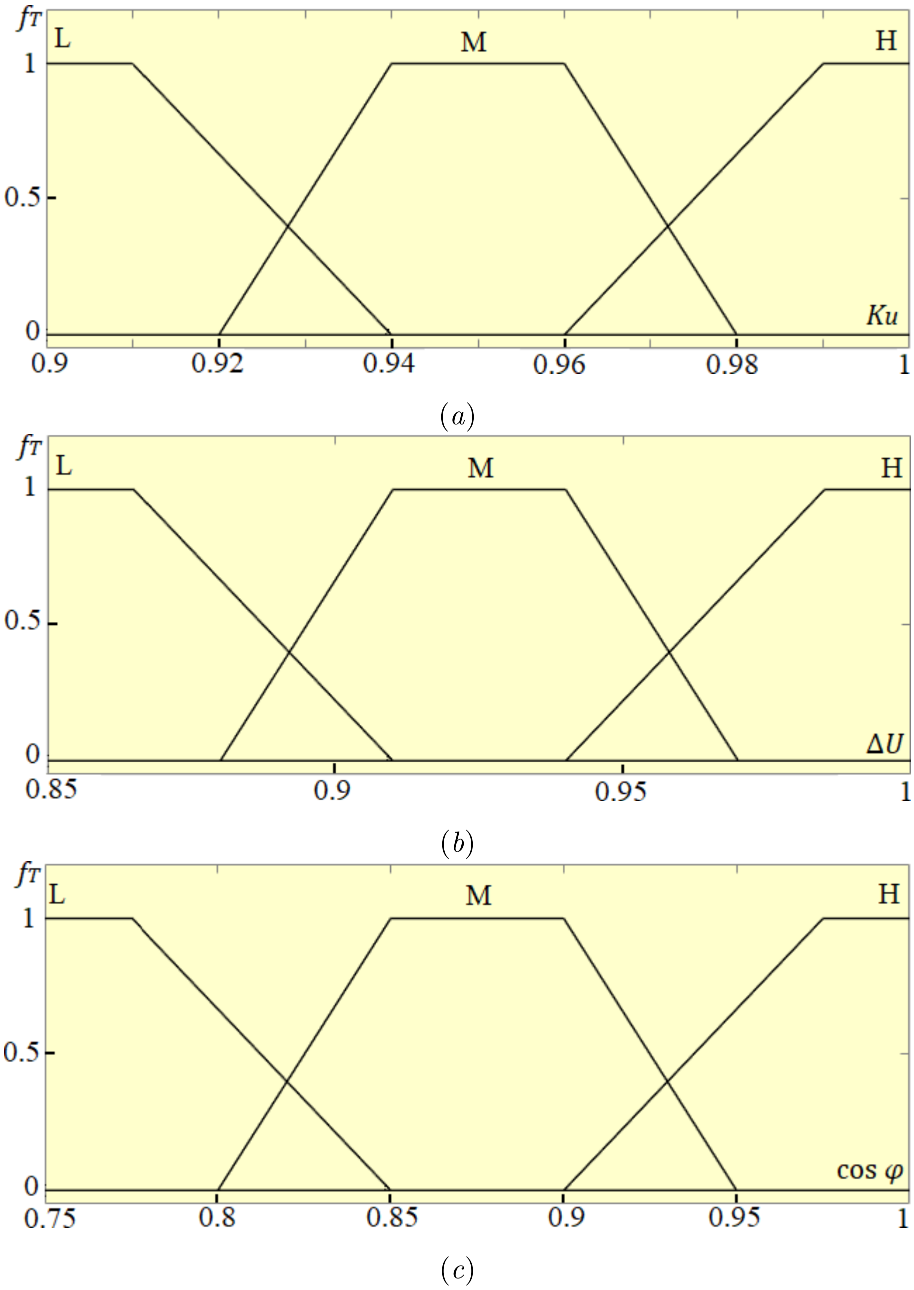


Figure 4. Graphs of the trapezoidal membership function for variables $Ku(a)$, $\Delta U(b)$, $\cos\varphi(c)$.

Considering the respective possibility of occurrence and the level of consequence of the realization of factors, the results of building fuzzy logic are obtained. In this case, they are based on the identified 27 rules. To analyze the results of the model, a graphical interpretation of the rules was made. This made it possible to see how the model works for the three output parameters Ku, ΔU, $\cos\varphi$ (figure 7).

The level of integration of RES into the electricity supply system reflects how efficiently and reliably the grid is provided with energy from RES. The integration of RES into the electricity supply system can have different levels, depending on the type and capacity of the installed equipment of these sources, as well as on the size and characteristics of the electricity grid.

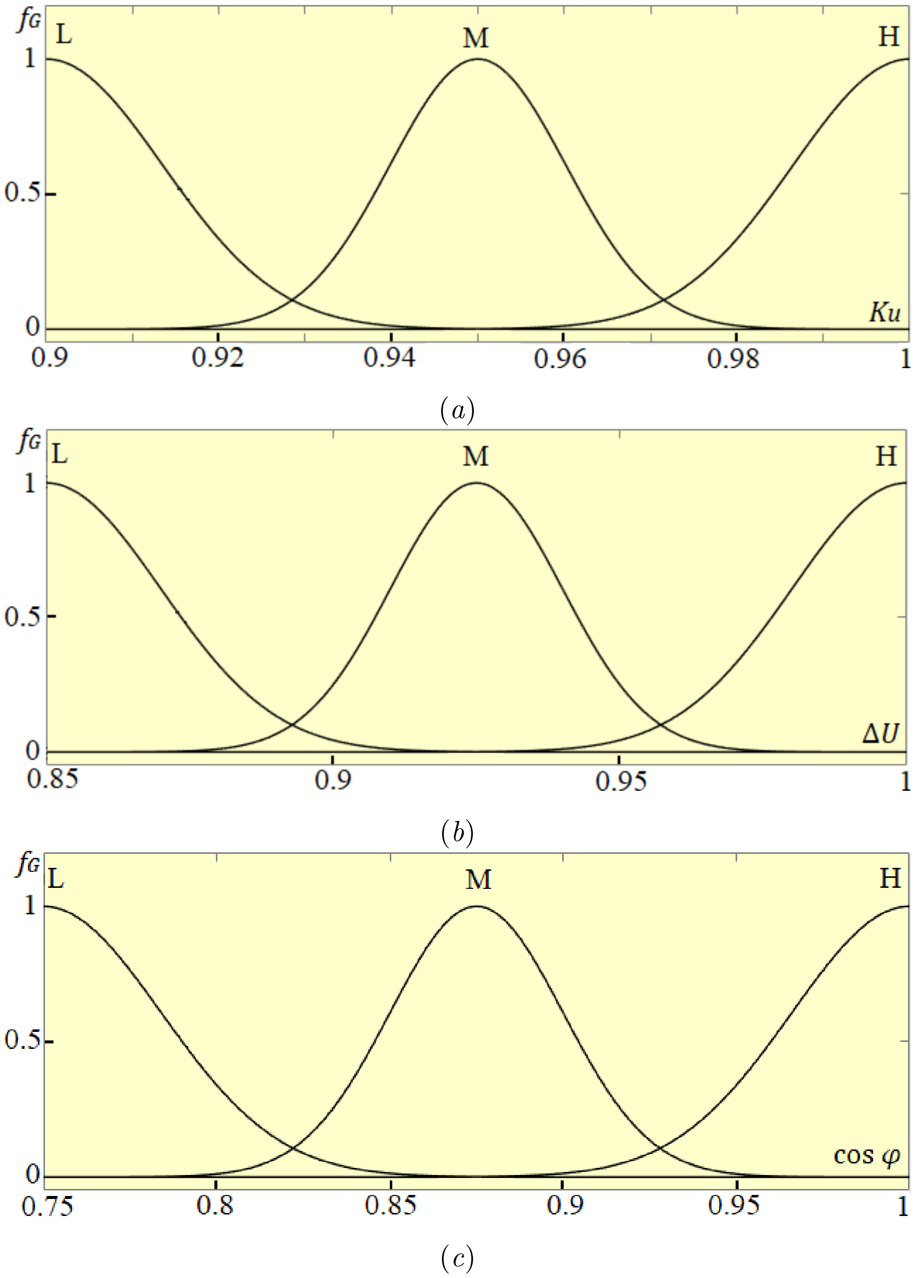


Figure 5. Graphs of a simple Gaussian function membership function for variables $Ku(a)$, $\Delta U(b)$, $\cos\varphi(c)$.

According to the results, the level of integration at the same values of the system parameters for the three selected membership functions is in a small range of deviations. For the triangular membership function with relative values Ku=0.94, ΔU=0.95, $\cos\varphi$=0.92, the level of integration is 0.763, for the trapezoidal function – 0.757, and for the simple Gaussian function it is 0.725. The small range of deviations indicates the adequacy of the developed model.

It should be noted that the method used allows us to track the level of RES integration at different values of system parameters. For example, for a triangular membership function with other parameter values (Ku=0.91, ΔU=0.92, $\cos\varphi$=0.91), the integration rate decreases to 0.537. That is, a mechanism for making a generalized decision when integrating renewable

1. If (Ku is L) and (ΔU is L) and (cos_φ is L) then (level_of_integrarion is L) (0.832)
2. If (Ku is L) and (ΔU is L) and (cos_φ is M) then (level_of_integrarion is M) (0.727)
3. If (Ku is L) and (ΔU is L) and (cos_φ is H) then (level_of_integrarion is M) (0.902)
4. If (Ku is M) and (ΔU is L) and (cos_φ is L) then (level_of_integrarion is M) (0.672)
5. If (Ku is M) and (ΔU is L) and (cos_φ is M) then (level_of_integrarion is M) (0.844)
6. If (Ku is M) and (ΔU is L) and (cos_φ is H) then (level_of_integrarion is H) (0.764)
7. If (Ku is H) and (ΔU is L) and (cos_φ is L) then (level_of_integrarion is M) (0.792)
8. If (Ku is H) and (ΔU is L) and (cos_φ is M) then (level_of_integrarion is M) (0.964)
9. If (Ku is H) and (ΔU is L) and (cos_φ is H) then (level_of_integrarion is H) (0.855)
10. If (Ku is L) and (ΔU is M) and (cos_φ is L) then (level_of_integrarion is M) (0.817)
11. If (Ku is L) and (ΔU is M) and (cos_φ is M) then (level_of_integrarion is M) (0.989)
12. If (Ku is L) and (ΔU is M) and (cos_φ is H) then (level_of_integrarion is H) (0.873)
13. If (Ku is M) and (ΔU is M) and (cos_φ is L) then (level_of_integrarion is M) (0.934)
14. If (Ku is M) and (ΔU is M) and (cos_φ is M) then (level_of_integrarion is H) (0.83)
15. If (Ku is M) and (ΔU is M) and (cos_φ is H) then (level_of_integrarion is H) (0.961)
16. If (Ku is H) and (ΔU is M) and (cos_φ is L) then (level_of_integrarion is H) (0.791)
17. If (Ku is H) and (ΔU is M) and (cos_φ is M) then (level_of_integrarion is H) (0.92)
18. If (Ku is H) and (ΔU is M) and (cos_φ is H) then (level_of_integrarion is VH) (0.84)
19. If (Ku is L) and (ΔU is H) and (cos_φ is L) then (level_of_integrarion is H) (0.811)
20. If (Ku is L) and (ΔU is H) and (cos_φ is M) then (level_of_integrarion is H) (0.94)
21. If (Ku is L) and (ΔU is H) and (cos_φ is H) then (level_of_integrarion is VH) (0.857)
22. If (Ku is M) and (ΔU is H) and (cos_φ is L) then (level_of_integrarion is H) (0.899)
23. If (Ku is M) and (ΔU is H) and (cos_φ is M) then (level_of_integrarion is VH) (0.823)
24. If (Ku is M) and (ΔU is H) and (cos_φ is H) then (level_of_integrarion is VH) (0.928)
25. If (Ku is H) and (ΔU is H) and (cos_φ is L) then (level_of_integrarion is H) (0.989)
26. If (Ku is H) and (ΔU is H) and (cos_φ is M) then (level_of_integrarion is VH) (0.895)
27. If (Ku is H) and (ΔU is H) and (cos_φ is H) then (level_of_integrarion is VH) (1)

Figure 6. Fuzzy logic rule base

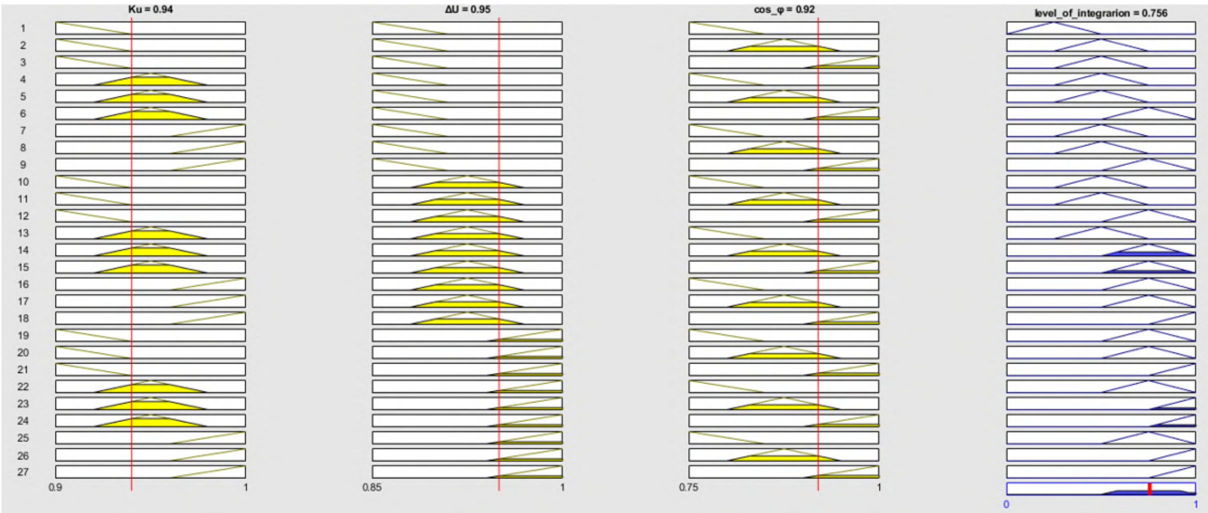


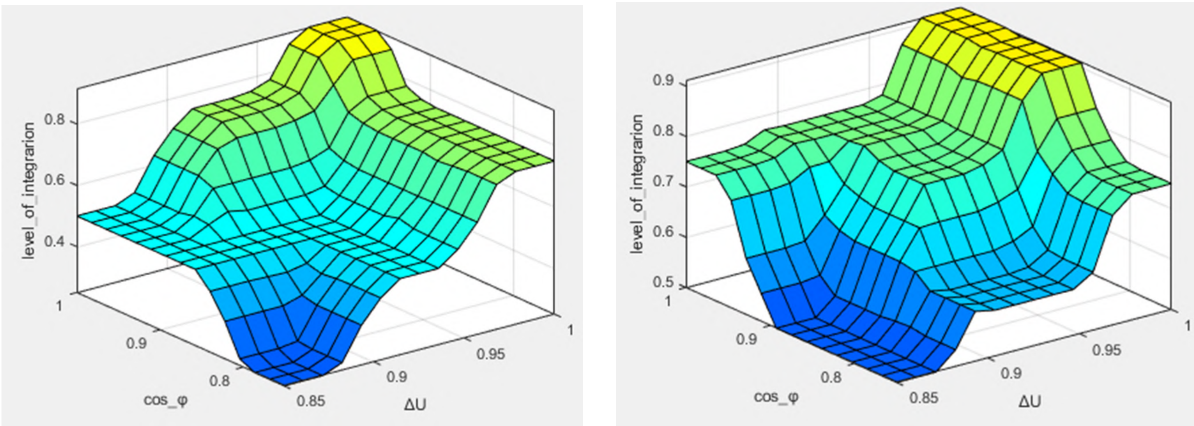
Figure 7. Results of calculating fuzzy logic for 27 rules of the triangular membership function.

energy sources into the power supply system appears. In the future, this will be used to develop a methodology for the controlled and efficient development of renewable energy.

The Matlab functionality makes it possible to view the input-output surface corresponding to the synthesized fuzzy system. However, when we go beyond the three dimensions, we begin to face problems with the full display of the results. Since our system has three inputs and one output, the program can only generate a three-dimensional output surface where any two inputs change, but one of the inputs must remain constant (figures 8-10).

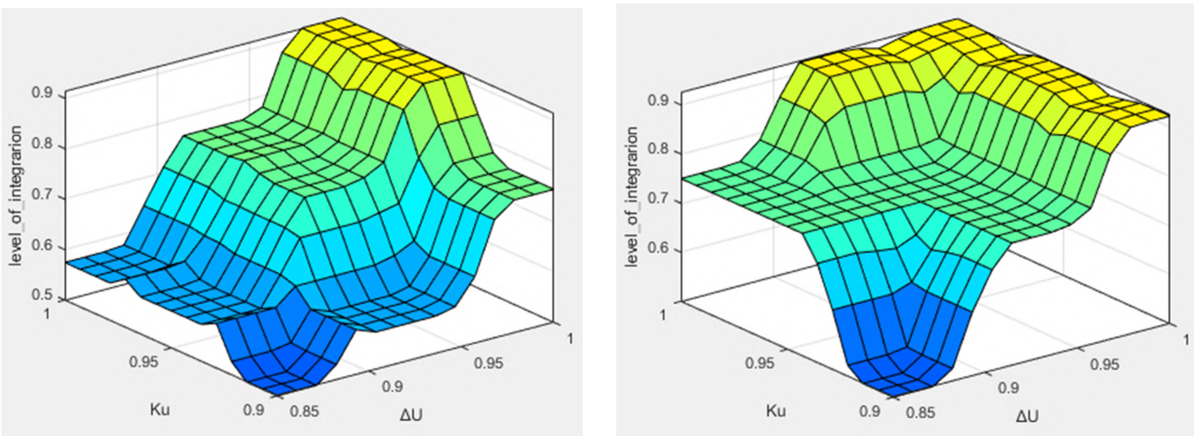
The fuzzy inference surface makes it possible to visually assess the probabilities of a situation that may result from the connection of a particular RES installation. In order to obtain the highest efficiency of RES, it is necessary to adhere to the parameters that form the yellow and green zones of the profile. The blue zone, on the contrary, is characterized by the greatest risks to the normal functioning of the system and shows a categorically unacceptable integration of the system and RES under these parameters. Getting into the blue zone is also not recommended, as it shows low efficiency from RES and a higher probability of risk consequences. The graphs have a local decrease in the level of integration, which is explained by the number of logical variables and rules. With their increase, the model will more accurately reflect the level of integration for making decisions on RES connection, which will be done in further research.

The developed system makes it possible to quickly carry out the evaluation procedure based on fuzzy logic tools and quantify the level of integration. It can also be supplemented or modified by an expert by introducing other rules, adjusting membership functions for variables,



(*a*) (*b*)

Figure 8. The fuzzy inference surface of the trapezoidal membership function with input parameters ΔU, $\cos\varphi$ at $Ku = 0.92$ (a) and $Ku = 0.97$ (b).



(*a*) (*b*)

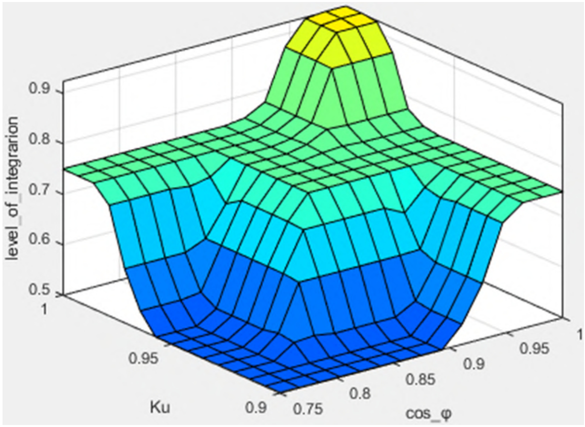
Figure 9. The fuzzy inference surface of the trapezoidal membership function with input parameters ΔU, Ku at $\cos\varphi = 0.92$ (a) and $\cos\varphi = 0.97$ (b).

and adding new parameters. Therefore, using this toolkit based on logical rules, it is possible to model various connection options, and then use the data obtained to set requirements for the parameters of the electrical installation at the stage of issuing technical specifications to the customer.

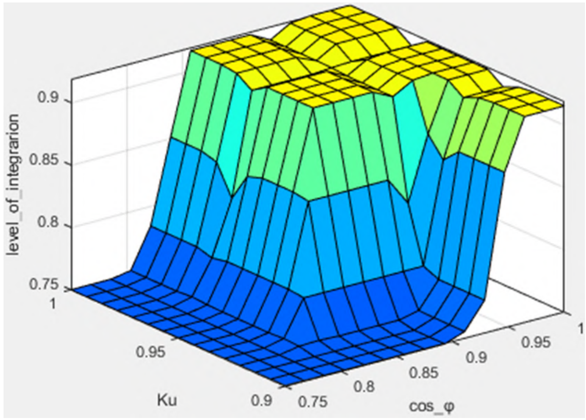
The results of the fuzzy logic system in the Matlab environment show that the program tools allow tracking the level of RES integration at different values of system parameters. The modeling results demonstrate the adequacy of the developed knowledge base and the possibility of its use for the controlled and efficient connection of renewable energy sources to power grids.

5. Conclusions

The growing role of intermittent generation from RES, the need to reduce the use of fossil fuels, and the different profile of consumer demand create a number of risks for the system. They relate to the impact of RES sources on the planning, organization of operation, and



(*a*)



(*b*)

Figure 10. The fuzzy inference surface of the trapezoidal membership function with input parameters Ku, $\cos\varphi$ at $\Delta U = 0.92$ (a) and $\Delta U = 0.97$ (b).

management of power grids. At present, the construction of clean energy generation facilities is carried out solely from the standpoint of commercial attractiveness, not from the standpoint of the country's economic development, environmental friendliness and consumer interests. The rapid development of "green" energy is taking place without considering the real needs of Ukraine's energy sector for additional generating capacity, which may lead to destabilization of the country's energy system and the possibility of emergencies.

In the tasks of risk assessment in connection of RES and decision-making under uncertainty, problems arise that are difficult to solve using traditional methods. In a real-world model, there is always a technological scatter of parameters due to the complexity of the system. To solve this problem, it is necessary to apply the mathematical apparatus of fuzzy logic theory. One of the most important advantages of this method is the ability to use the experience of an expert without drawing up differential equations.

We have developed a fuzzy model for risk assessment in the integration of RES into the electricity supply system based on expert data. To formalize the initial data, we used triangular, trapezoidal, and simple Gaussian membership functions for the input variables. According to the results, the level of integration at the same values of the system parameters for the three selected membership functions is in a small range of deviations, which indicates the adequacy of the developed model. In the future, it can be supplemented or modified by an expert by introducing other rules, adjusting the membership functions for the variables, and adding new parameters.

The use of fuzzy logic allows tracking the level of RES integration at different values of system parameters. The toolkit, based on logical rules, allows modeling various connection options. The data obtained can then be used to set requirements for the parameters of the electrical installation at the stage of issuing technical specifications to the customer. The modeling results demonstrate the adequacy of the developed knowledge base and the possibility of its use for the controlled and efficient connection of renewable energy sources to power grids.

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References

[1] IRENA 2022 Renewable Capacity Statistics 2022 Tech. rep. International Renewable Energy Agency Abu Dhabi URL https://www.irena.org/publications/2022/Apr/Renewable-Capacity-Statistics-2022
[2] Avenston Group 2022 Statystyka svitovoho rynku VDE za 2021 rik vid IRENA [Statistics of the global renewable energy market for 2021 from IRENA] URL https://avenston.com/articles/renewable-capacity-2021/
[3] Stepanenko V, Zamulko A, Veremiichuk Y and Nakhodov V 2022 *POWER ENGINEERING: economics, technique, ecology* **68**(2) 64–74 ISSN 1813-5420 URL https://doi.org/10.20535/1813-5420.2.2022.261372
[4] Veremiichuk Y, Zamulko A, Zaichenko S, Mahnitko A, Berzina K and Zicmane I 2018 Analysis of Electric Energy Supply Security Attached to Renewable Energy Sources Implementation *2018 International Conference and Exposition on Electrical And Power Engineering (EPE)* pp 0977–0981 URL https://doi.org/10.1109/ICEPE.2018.8559840
[5] Courtecuisse V, Sprooten J, Robyns B, Petit M, Francois B and Deuse J 2010 *Mathematics and Computers in Simulation* **81**(2) 208–224 ISSN 0378-4754 Modelling and Simulation of Electrical Machines, Converters and Power Systems URL https://doi.org/10.1016/j.matcom.2010.03.003
[6] Dimitroulis P and Alamaniotis M 2022 *Electric Power Systems Research* **202** 107621 ISSN 0378-7796 URL https://doi.org/10.1016/j.epsr.2021.107621
[7] Liu W, Xu Y, Feng X and Wang Y 2022 *International Journal of Electrical Power & Energy Systems* **139** 107867 ISSN 0142-0615 URL https://doi.org/10.1016/j.ijepes.2021.107867
[8] Yahyaoui I, Sallem S, Kamoun M B A and Tadeo F 2014 *Energy Conversion and Management* **78** 835–842 ISSN 0196-8904 URL https://doi.org/10.1016/j.enconman.2013.07.091
[9] Ziemba P 2021 *Energies* **14**(4) 978 URL https://doi.org/10.3390/en14040978
[10] Pankovits P, Abbes D, Saudemont C, Brisset S, Pouget J and Robyns B 2016 *Mathematics and Computers in Simulation* **130** 236–250 ISSN 0378-4754 11th International Conference on Modeling and Simulation of Electric Machines, Converters and Systems URL https://doi.org/10.1016/j.matcom.2016.05.002
[11] de Carvalho W C, Bataglioli R P, Fernandes R A S and Coury D V 2020 *Electric Power Systems Research* **184** 106287 ISSN 0378-7796 URL https://doi.org/10.1016/j.epsr.2020.106287
[12] Baqui M N 2012 Fuzzy decision model for a smart grid URL https://library.ndsu.edu/ir/handle/10365/19396
[13] Ibrahim O, Bakare M S, Amosa T I, Otuoze A O, Owonikoko W O, Ali E M, Adesina L M and Ogunbiyi O 2023 *Energy Conversion and Management: X* **18** 100354 ISSN 2590-1745 URL https://doi.org/10.1016/j.ecmx.2023.100354
[14] Castillo-Calzadilla T, Garay-Martinez R and Andonegui C M 2023 *Sustainable Cities and Society* **89** 104375 ISSN 2210-6707 URL https://doi.org/10.1016/j.scs.2022.104375
[15] Lewis S M, Fitts G, Kelly M and Dale L 2014 *Computers and Electronics in Agriculture* **103** 39–47 ISSN 0168-1699 URL https://doi.org/10.1016/j.compag.2014.02.006
[16] Alekhya G B S, Shashikanth K and Prasad M A 2022 *Materials Today: Proceedings* **62** 1803–1810 ISSN 2214-7853 International Conference on Design, Manufacturing and Materials Engineering URL https://doi.org/10.1016/j.matpr.2021.12.415
[17] Zhai P and Williams E D 2012 *Renewable Energy* **41** 350–357 ISSN 0960-1481 URL https://doi.org/10.1016/j.renene.2011.11.041
[18] Zadeh L A and Aliev R A 2018 *Fuzzy Logic Theory and Applications* (Singapore: World Scientific Publishing) URL https://doi.org/10.1142/10936
[19] Nguyen H T, Walker C and Walker E A 2018 *A first course in fuzzy logic* 4th ed (New York: Chapman and Hall/CRC)
[20] The MathWorks, Inc 2023 Fuzzy Logic Toolbox: Design and simulate fuzzy logic systems URL https://www.mathworks.com/products/fuzzy-logic.html
[21] Jain A and Sharma A 2020 *Journal of Critical Reviews* **7**(19) 8717–8733 URL https://tinyurl.com/yf7fahnf

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The influence of electric transportation charging modes on the operation of the Ukraine's Integrated Electricity System and emission levels

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The influence of electric transportation charging modes on the operation of the Ukraine's Integrated Electricity System and emission levels

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Abstract. This paper studies the potential impact of electric transportation charging modes on Ukraine's Integrated Power System operation and emission levels. The non-linear integer least-cost model developed by the Institute of General Energy was used. Three electric transportation charging modes were analyzed. Calculations illustrate mainly positive effect of electric transportation on the energy system operation, particularly reduction of fuel consumption and emissions of greenhouse gases and pollutants. The results would support the development of strategies for electric transportation development.

1. Introduction

Nowadays the humankind is facing the dramatic challenges – the limited technologically available resources of fossil fuels and global climate change. Implementation of electric transportation is effective way to address these problems. Naturally, the part of electricity is produced from fossil fuel combustion, but there are alternative sources of electric energy integrated in national power systems, i.e. nuclear energy, hydro, wind, solar and other renewable sources. Also it should be noted that electric transportation charging stations equipped by solar batteries do not use any fossil fuel and do not produce any greenhouse gases (GHG) and pollutant emissions.

The fleet of electric transportation (ET) rapidly increases worldwide [1, 2]. The number of electric vehicles per 1,000 residents in EU significantly varies. For example, in 2020 this indicator totals 6.5 in France, 8.5 in Germany, 20.6 in Sweden and 81 in Norway. Ukraine is significantly behind in the number of electric cars (approximately 0.75 numbers of electric vehicles per 1,000 residents). Now Ukrainian government plans to develop national strategy and programs for electric transportation implementation.

The common practice is to compare emissions from ET with petrol cars using average consumption of electricity/fuel per 1 km and specific emissions of GHG and pollutants from electricity/fuel [3–6]. Similar approach is used for evaluating economic efficiency of electric vehicles exploitation. This approach is not comprehensive. We should take into account that ET charging is additional load on energy system operation. Therefore electric transportation causes changes in energy system operation and consequently changes in the emission level.

Although ET presents several environmental advantages, a massive introduction of them could create several issues in the power grid, which has been studied by several researchers [7]. For example, in [8], the impact of different penetration levels of plug-in electric vehicles in a distribution system was considered, and it was demonstrated that a significant ET load leads to voltage drop and voltage deviations. In [9], it was demonstrated that charging ET considerably increases the distribution load and, so, the total power losses. Furthermore, ET charging increases the daily peak load. Shafiee et al [10] indicated that ET generate substantial investment costs in distribution systems, and that power losses can reach up to 40 percents for an EV penetration of 62 percents. Lucas et al [11] exposed that ET fast charging leads to harmonic issues and failure to respect IEEE standard limits. Turker et al [12] proposed that the life durations of low-voltage transformers are reduced with a high penetration of ET.

Although ET presents several environmental advantages, a massive introduction of them could create several issues in the power grid, which has been clarified by Clairand et al [7]. For example, smart charging of ET is an important area of study, which allows EV users and grid operators to properly manage ET charging profiles in order to obtain technical and economic benefits, as well as considering the specific demand-side management of ET [13]. Some other researchers have focused on the management of ET charging stations. In particular, it is crucial to locate the optimal placement of ET charging stations to meet technical grid constraints, considering customer wait times [14, 15].

So the fundamental study of the influence of electric transportation implementation on Ukraine's Integrated Power System (IPS) is needed for developing strategies of ET fleet increase. The experience of other countries is not applicable for Ukrainian circumstances. The Ukraine's IPS is unique complex system with different energy sources, partly obsolete equipment etc.

The main factors to consider are the volume of ET and ET charging modes. The specific feature of electric transportation is the opportunity to vary the charging load during the day due to implementing different regulatory and/or incentive measures.

The *aim* of the paper is to estimate the effect of different ET charging modes on the IES operation, fossil fuel consumption, GHG and pollutant emissions.

2. Methodology

Author use program and information complex simulating the operation of Ukraine's Integrated Power System developed in the Institute of General Energy of the National Academy of Sciences of Ukraine [16].

This complex is based on non-linear mixed integer least-cost dispatch model. It contains information of all power units in the Ukraine's IPS mentioned below.

Nuclear energy provides a reliable base load and covers more than half of the electricity production in Ukraine (55.5% in 2021). There are four nuclear power plants (NPPs) in Ukraine with a total installed capacity of 13,835 megawatt (MW) (15 reactors in total, including 13 reactors with a capacity of 1,000 MW and two reactors with a capacity of 415 MW and 420 MW, respectively) [17].

At the beginning of 2022, there were 12 thermal power plants (TPPs) in Ukraine with a total installed power capacity of 21.5 gigawatt (GW). Most TPPs are using coal as a primary fuel. In 2021, the TPPs' share in electricity production was 23.8% [18]. At the beginning of 2022, the total installed power capacity of combined heat and power plants (CHPs) was 6.1 GW. Most CHPs are using natural gas as a primary fuel. In 2021 the share of CHPs and cogeneration units in electricity production was 5.5%.

At the beginning of 2022, there were ten large hydropower plants (HPPs) with a total installed power capacity of about 4.7 GW (101 units in total) and three pumped storage plants (PSPs) with an installed capacity of 1.5 GW (11 units ranging from 33 MW to 324 MW per unit). Hydropower plays a crucial role in the functioning of the Ukrainian power system, as HPPs and PSPs are the main providers of auxiliary services to meet the peak demand of the power system and balance intermittent Renewable Energy Source (RES) capacities. PSPs also contribute to flattening the night "gaps" of electricity consumption. In 2021, the share of HPPs and PSPs in electricity production was 5.8% and 0.8%, respectively [19].

The photovoltaic (PV) sector had the highest growth rate among other renewable energy sources in Ukraine during 2019-2021. At the beginning of 2022, the total installed PV capacity reached 7.6 GW or 80% of the total RES installed capacity in Ukraine (including 45,000 prosumer installations with a total capacity of 1.2 GW) [20].

At the beginning of 2022, Ukraine's total installed capacity of wind power plants (all onshore) was 1.6 GW. Almost all wind power plants in Ukraine were built in the southern regions nearby the Azov and Black seas coasts (Kherson and Zaporizhzhia regions), where natural conditions

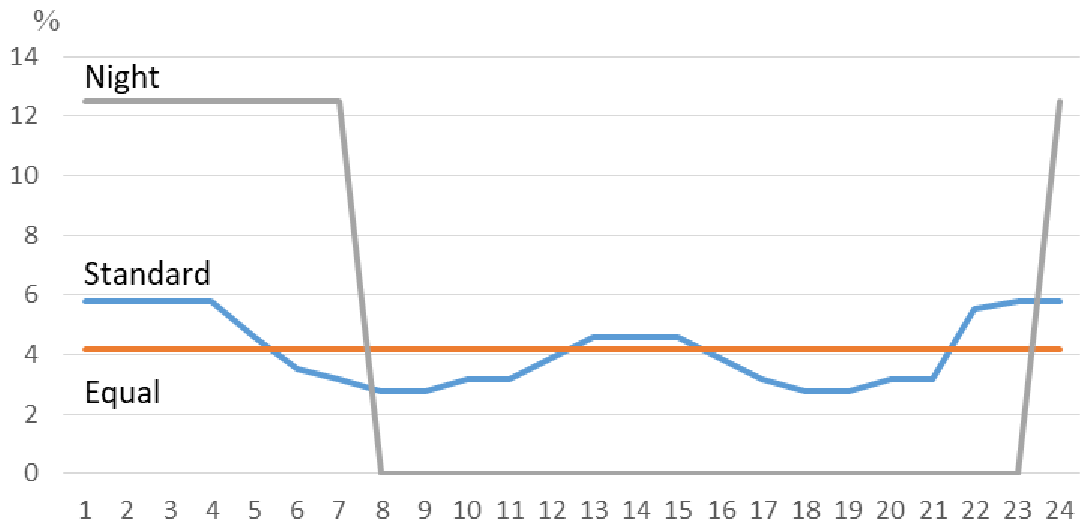

Figure 1. Electric transportation charging modes.

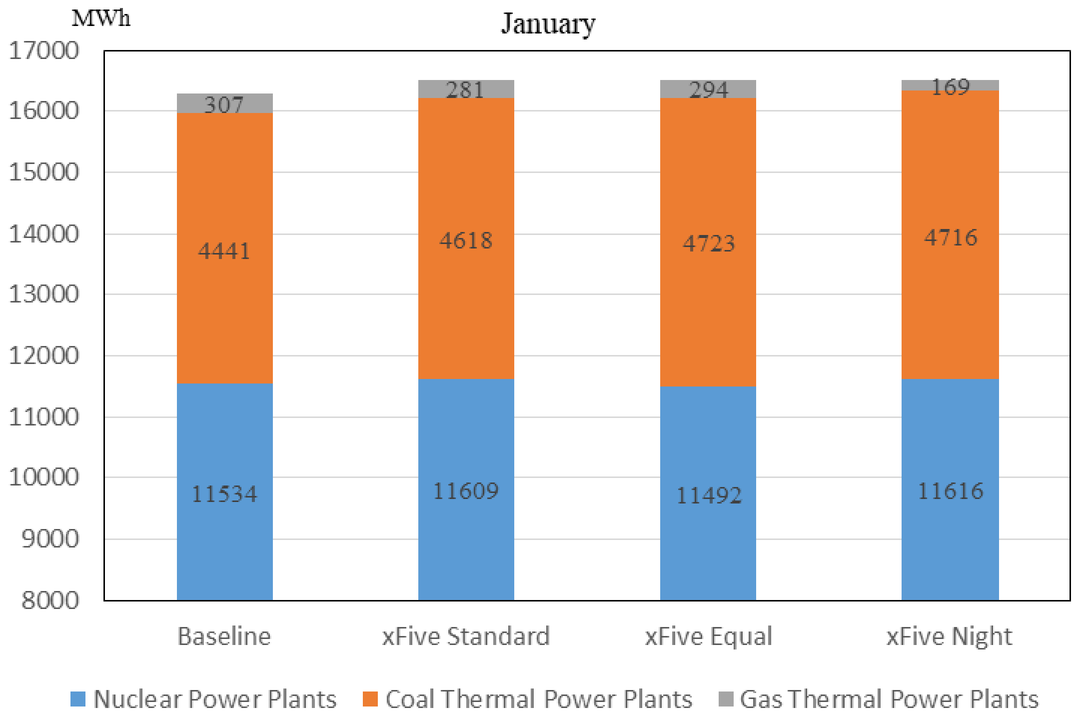

Figure 2. Structure of Ukraine's IPS operation in January.

for wind power plants are the most favorable.

A set of calculations was carried out for assessing influence of electric transportation charging modes on Ukraine's IPS functioning, fuel combustion and emissions of carbon dioxide and

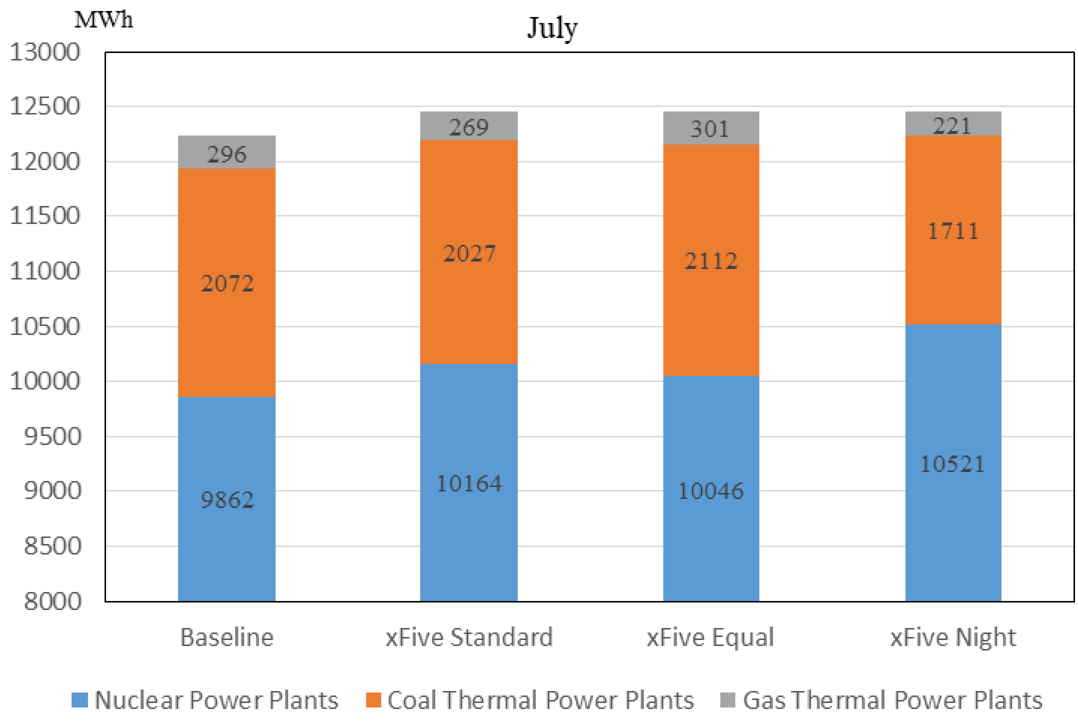

Figure 3. Structure of Ukraine's IPS operation in July.

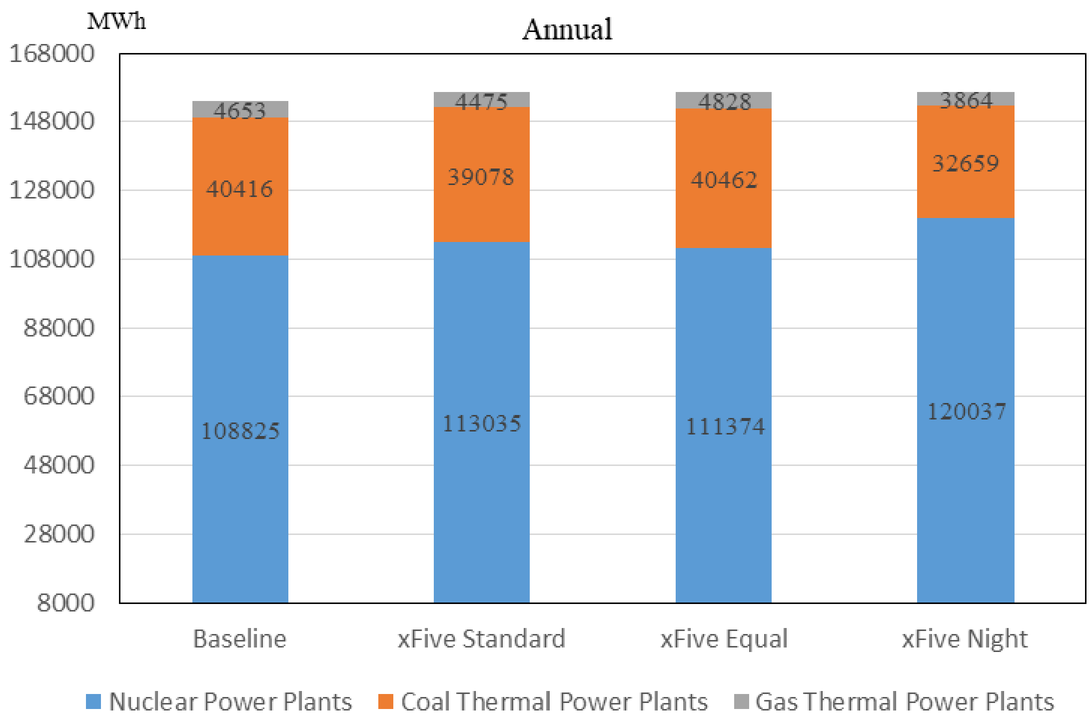

Figure 4. Annual Structure of Ukraine's IPS operation.

pollutants.

Four scenarios were considered. First scenario assumes the ET fleet at the 2020 level (Baseline). Next three scenarios assume that a number of EV in Ukraine increases by five times and consider three charging modes; standard (xFive Standard), equal (xFive Equal) and night (xFive Night) (figure 1). Evidently, two last modes are ideal and not achievable really. However, the results indicate the direction for development of strategy and regulatory acts to get better results.

3. Results

Diagrams at the figure 2, figure 3 and figure 4 illustrates structure of Ukraine‘s IPS operation under four scenarios in January, July and annual. Author choose January and July, because usually these months differ each other significantly in consumption level, as well as wind, solar and hydro characteristics.

The results show that the share of nuclear power plants increases practically for all scenarios except for the scenario xFive Equal in Winter. Therefore it is expected the decrease of fuel consumption as well as GHG and pollutants emissions. The table 1 (January), table 2 (July) and table 3 (annual) illustrate this fact. The figure 5 and figure 6 show the behavior of fuel

Table 1. Fuel combustion and emissions in January.

Indicators	*Units*	*Baseline*	*xFive Standard*	*xFive Equal*	*xFive Night*
Electricity produced	MWh	19459.6	19689.4	19689.4	19689.4
Fuel combusted	thous. tce	2498.6	2559.3	2606.1	2564.7
Fuel intensity	tce/kWh	0.128	0.130	0.132	0.130
Compared to baseline	Percent	100.00	101.24	103.09	101.45
CO_2 Emissions	Gg	6184.1	6361.0	6487.2	6411.4
Compared to baseline	Percent	100.0	102.9	104.9	103.7
Specific CO_2 Emissions	t/kWh	0.318	0.323	0.329	0.326
SO_2 Emissions	Gg	16.391	16.985	17.366	17.300
NO_x Emissions	Gg	4.034	4.213	4.260	4.326
Dust	Gg	0.858	0.889	0.909	0.906

Table 2. Fuel combustion and emissions in July.

Indicators	*Units*	*Baseline*	*xFive Standard*	*xFive Equal*	*xFive Night*
Electricity produced	MWh	14469.7	14699.5	14699.5	14699.5
Fuel combusted	thous. tce	1113.4	1087.1	1130.3	945.1
Fuel intensity	tce/kWh	0.077	0.074	0.077	0.064
Compared to baseline	Percent	100.00	96.12	99.94	83.56
CO_2 Emissions	Gg	2795.4	2731.2	2841.0	2351.4
Compared to baseline	Percent	100.0	97.7	101.6	84.1
Specific CO_2 Emissions	t/kWh	0.193	0.186	0.193	0.160
SO_2 Emissions	Gg	7.573	7.408	7.710	6.277
NO_x Emissions	Gg	1.668	1.642	1.699	1.456
Dust	Gg	0.398	0.389	0.405	0.329

Table 3. Fuel combustion and emissions annual.

Indicators	*Units*	*Baseline*	*xFive Standard*	*xFive Equal*	*xFive Night*
Electricity produced	MWh	190881.3	193586.9	193586.9	193586.9
Fuel combusted	thous. tce	22231.9	21629.5	22283.8	18863.1
Fuel intensity	tce/kWh	0.116	0.112	0.115	0.097
Compared to baseline	Percent	100.00	95.93	98.83	83.66
CO_2 Emissions	Gg	55437.3	53822.9	55534.0	46327.6
Compared to baseline	Percent	100.0	97.1	100.2	83.6
Specific CO_2 Emissions	t/kWh	0.290	0.278	0.287	0.239
SO_2 Emissions	Gg	148.596	143.766	148.689	120.971
NO_x Emissions	Gg	33.730	33.038	33.923	28.962
Dust	Gg	7.797	7.541	7.802	6.330

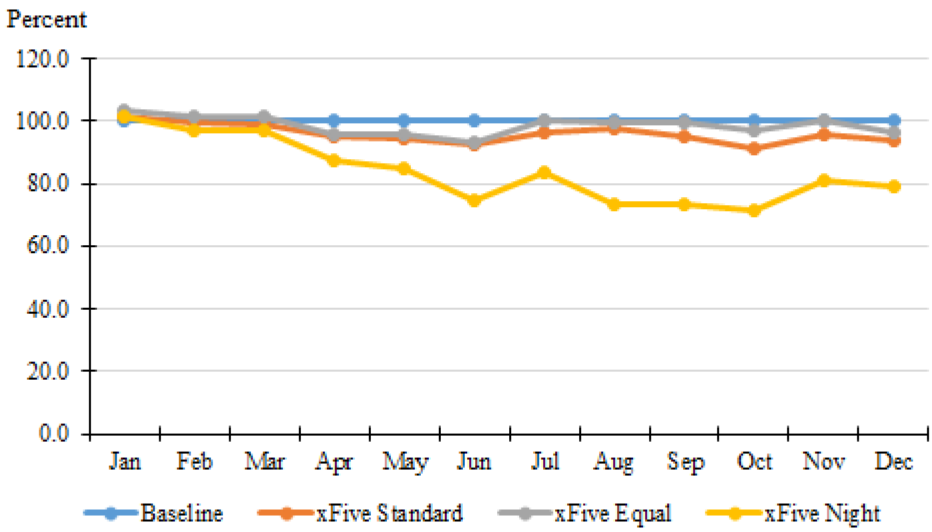

Figure 5. Energy intensity compared to baseline.

intensity and carbon dioxide emissions throughout the year. Fuel intensity increases in Winter for all scenarios, because the share of ET load is smaller than in Summer. In Summer and annually the decrease of of fuel intensity and emissions reaches up to approximately 14 percent (xFive Night). For scenario xFive Equal GHG and pollutant emissions increase despite of decrease of fuel intensity. This is explained by the larger share of coal thermal power plants compared to gas thermal power plants. It should be noted that such trends are observed exclusively for Ukraine due to specific structure of Ukraine's with the large share of nuclear energy.

4. Conclusions

Electric transportation (ET) volumes rapidly increase around the world. Ukrainian government also plans to develop strategies for ET implementation. For these purposes, it is necessary to study the influence of ET as additional load on Ukraine's Integrated Energy System operation. The main factors to consider are the volume of ET and ET charging modes.

ET implementation may affect both positively and negatively the IES operation depending on the share of additional ET load. The calculations were carried out using information and

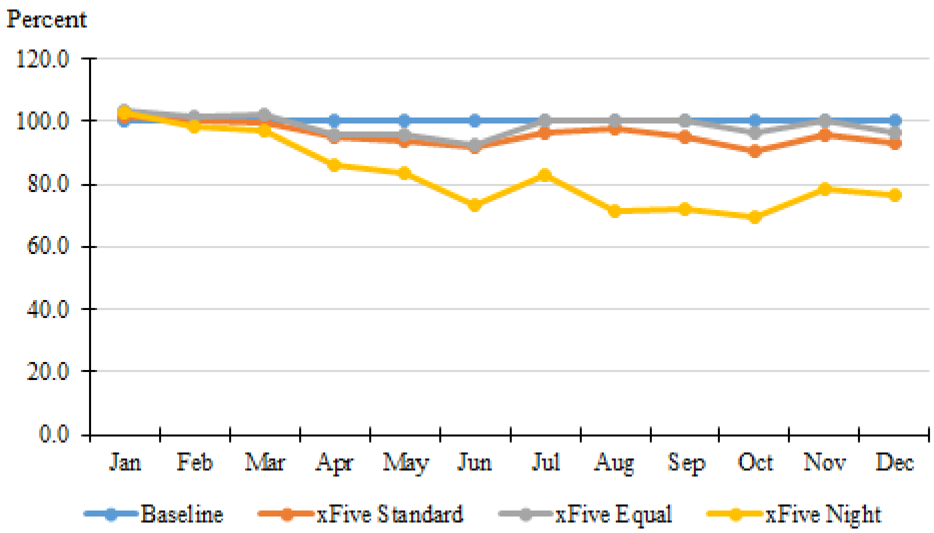

Figure 6. Carbon dioxide emissions compared to baseline.

program complex developed in the Institute of General Energy. This paper analyzed the influence of ET charging modes on fuel consumed by IES, fuel intensity and emissions levels. Three charging modes were considered, specifically standard, night and equal. Evidently, two last modes are ideal and not achievable really. However, the results indicate the direction for development of strategy and regulatory acts to get better results.

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References

[1] 2023 Vehicles in Use Europe 2023 Tech. rep. European Automobile Manufacturers' Association URL https://www.acea.auto/files/ACEA-report-vehicles-in-use-europe-2023.pdf
[2] Muratori M, Alexander M, Arent D, Bazilian M, Cazzola P, Dede E M, Farrell J, Gearhart C, Greene D, Jenn A, Keyser M, Lipman T, Narumanchi S, Pesaran A, Sioshansi R, Suomalainen E, Tal G, Walkowicz K and Ward J 2021 *Progress in Energy* **3**(2) 022002 URL https://doi.org/10.1088/2516-1083/abe0ad
[3] Bieker G 2021 A Global Comparison of the Life-Cycle Greenhouse Gas Emissions of Passenger Cars White Paper International Council on Clean Transportation Europe Berlin URL https://theicct.org/wp-content/uploads/2021/07/Global-Vehicle-LCA-White-Paper-A4-revised-v2.pdf
[4] Moomaw W, Burgherr P, Heath G, Lenzen M, Nyboer G and Verbruggen A 2012 Annex II: Methodology *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation* ed Edenhofer O, Madruga R P, Sokona Y, Seyboth K, Matschoss P, Kadner S, Zwickel T, Eickemeier P, Hansen G, Schlömer S and von Stechow C (New York, NY: Cambridge University Press) pp 973–1000 URL https://www.ipcc.ch/site/assets/uploads/2018/03/SRREN_Full_Report-1.pdf
[5] Morita T, Robinson J, Adegbulugbe A, Alcamo J, Herbert D, Lebre la Rovere E, Nakicenivic N, Pitcher H, Raskin P, Riahi K, Sankovski A, Solkolov V, de Vries B and Zhou D 2001 Greenhouse Gas Emission Mitigation Scenarios and Implications *Climate Change 2001: Mitigation. A Report of Working Group III of the Intergovernmental Panel on Climate Change* (Cambridge University Press) pp 115–166
[6] Ellingsen L A W, Singh B and Strømman A H 2016 *Environmental Research Letters* **11**(5) 054010 URL https://doi.org/10.1088/1748-9326/11/5/054010
[7] Clairand J M, Guerra-Terán P, Serrano-Guerrero X, González-Rodríguez M and Escrivá-Escrivá G 2019 *Energies* **12**(16) 3114 ISSN 1996-1073 URL https://doi.org/10.3390/en12163114
[8] Clement-Nyns K, Haesen E and Driesen J 2010 *IEEE Transactions on Power Systems* **25**(1) 371–380 URL https://doi.org/10.1109/TPWRS.2009.2036481
[9] Shafiee S, Fotuhi-Firuzabad M and Rastegar M 2013 *IEEE Transactions on Smart Grid* **4**(3) 1351–1360 URL https://doi.org/10.1109/TSG.2013.2251483

[10] Shafiee S, Fotuhi-Firuzabad M and Rastegar M 2013 *IEEE Transactions on Smart Grid* **4**(3) 1351–1360 URL https://doi.org/10.1109/TSG.2013.2251483

[11] Lucas A, Bonavitacola F, Kotsakis E and Fulli G 2015 *Electric Power Systems Research* **127** 13–21 ISSN 0378-7796 URL https://doi.org/10.1016/j.epsr.2015.05.012

[12] Turker H, Bacha S, Chatroux D and Hably A 2012 *IEEE Transactions on Power Delivery* **27**(3) 1323–1331 URL https://doi.org/10.1109/TPWRD.2012.2193423

[13] Guille C and Gross G 2009 *Energy Policy* **37**(11) 4379–4390 ISSN 0301-4215 URL https://doi.org/10.1016/j.enpol.2009.05.053

[14] Oda T, Aziz M, Mitani T, Watanabe Y and Kashiwagi T 2018 *Sustainable Cities and Society* **36** 99–106 ISSN 2210-6707 URL https://doi.org/10.1016/j.scs.2017.10.024

[15] Arkin E M, Carmi P, Katz M J, Mitchell J S B and Segal M 2019 *Discrete Applied Mathematics* **254** 10–16 ISSN 0166-218X URL https://doi.org/10.1016/j.dam.2018.07.019

[16] Shulzhenko S V 2021 *The Problems of General Energy* **66**(3) 4–13 URL https://doi.org/10.15407/pge2021.03.004

[17] Shulzhenko S, Turutiukov O and Bilenko M 2020 Mixed integer linear programming dispatch model for power system of Ukraine with large share of baseload nuclear and variable renewables *2020 IEEE 7th International Conference on Energy Smart Systems (ESS)* pp 363–368 URL https://doi.org/10.1109/ESS50319.2020.9160222

[18] Shulzhenko S V, Turutikov O I and Ivanenko N P 2021 *The Problems of General Energy* **60**(1) 11–23 URL https://doi.org/10.15407/pge2020.01.014

[19] Shulzhenko S V, Turutikov O I and Tarasenko P V 2019 *The Problems of General Energy* **59**(4) 13–23 URL https://doi.org/10.15407/pge2019.04.013

[20] Buratynskyi I, Nechaieva T, Shulzhenko S and Ivanenko N 2021 The Optimization of PV-plant's DC/AC Equipment Ratio Using the Non-linear Least-cost Model *2021 IEEE 3rd Ukraine Conference on Electrical and Computer Engineering (UKRCON)* pp 358–362 URL https://doi.org/10.1109/UKRCON53503.2021.9575720

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Automatic method of preparation of data for setting the model of the electric network mode when constructing the mnemonic diagram of the object for the simulator

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Automatic method of preparation of data for setting the model of the electric network mode when constructing the mnemonic diagram of the object for the simulator

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Abstract. The article is devoted to an automatic data preparation method for setting up a distribution network model, which is used to develop training tasks for distribution network personnel. The main goal in creating the method is to reduce the time for developing a simulator task by leveling the human error during the stage of filling in the structural data of the distribution network components. To interact with the automatic method and the already pre-created component library that was used in the previous method, it was necessary to change the internal structure of the double winding and three winding transformer components. Also, a new structural component was added to the library – Connection. The program algorithm of the automatic method consists of three cycles that go through all the components transferred from the library to the distribution network model. For a better understanding and perception of textual information about each cycle, a graphical representation of cycle process diagrams is presented. In conclusion, information is provided on the time spent when creating a task with manual data preparation and the developed automatic one, as well as suggestions to reduce computer resourced used during model run.

1. Automatic method of preparation of data

Rapid advances in technology have also affected the energy industry. In the components of energy distribution networks, characteristics and properties change dynamically, and the networks themselves undergo frequent changes in the number of components and structural changes. Given these changes, employees need to learn new knowledge and test current skills. The lack of skills and lack of qualifications of personnel in this area threatens the safety of people and the failure of networks [1, 2]. Accordingly, it was necessary to speed up the process of developing simulator tasks, as well as take into account innovations in the energy sector [3]. Significant results in this matter have been achieved with the help of the distribution network model.

The distribution network model is a program that was created using a graphical editor that contains a graphic field and a library of distribution network components with which it is possible to create a mnemonic diagram model that will completely duplicate the existing distribution network. The model can be run on any device with the Windows operating system, which is beneficial from an economic point of view [1, 4–6]. The model of distribution network modes does not require the presence of a programmer at the task development stage, since all the processes that require the programmer's work (calculation of current or voltage values, mode switching, functions of the distribution network components) were done before the task development stage [7–9]. Previously, the task was developed simultaneously by a programmer and an energy specialist who does not have programming skills, which significantly slowed down the development. A specialist in the energy field can contact a programmer to add a new distribution network component by providing the necessary technical documentation about the component. The new component will be added to the library from the next version of the model, and the developer of simulation tasks will be able to use the new components to train personnel.

At the stage of preparing data for calculating the model of the distribution network, initially, the developer manually enters the structural parameters (number of copies of components, branch indices). The main disadvantage of this method of preparing mode model setting data is the possibility of errors when entering this data. These errors can occur if the task developer copied a ready-made parameter, pasted it, but forgot to change the value to the required one. Therefore, several parameters will have the same values of node numbers or branch indices, which will lead to an error in calculating the mode values. It can take a long time to find invalid parameter values. An error in the calculation of modes makes this training task irrelevant in the process of training the personnel of the distribution network, which leads to a decrease in the competence of the personnel. Therefore, it was decided to develop a new data entry method that would eliminate the human factor in the process of entering structural parameters. This method has been called the automatic data entry method for setting up the mode model. Unlike manual preparation, in automatic preparation, a copy of the node component receives its number in the process of adding it to the mimic (the copy that was added first gets number 0, the copy that was added second gets number 1, etc.).

2. Library of components

As in manual data preparation, the automatic one uses a library of distribution network mnemonic diagram components, which is created by graphical editor. The library contains the following components (figure 1):

(i) Structural Components
- Node
- Branch
- Line
- Connection

(ii) Technological components
- Double winding transformer
- Three winding transformer
- Switch
- Disconnector

(iii) Output Components
- Current pointer
- Node load power pointer
- The field for outputting the value of the load current of the node
- Voltage value output field
- Current value output field

For automatic preparation, the following components of the mnemonic diagram have been changed: Double winding transformer and a three winding transformer. Also, a new structural component was added to the mnemonic diagram component library – a connection.

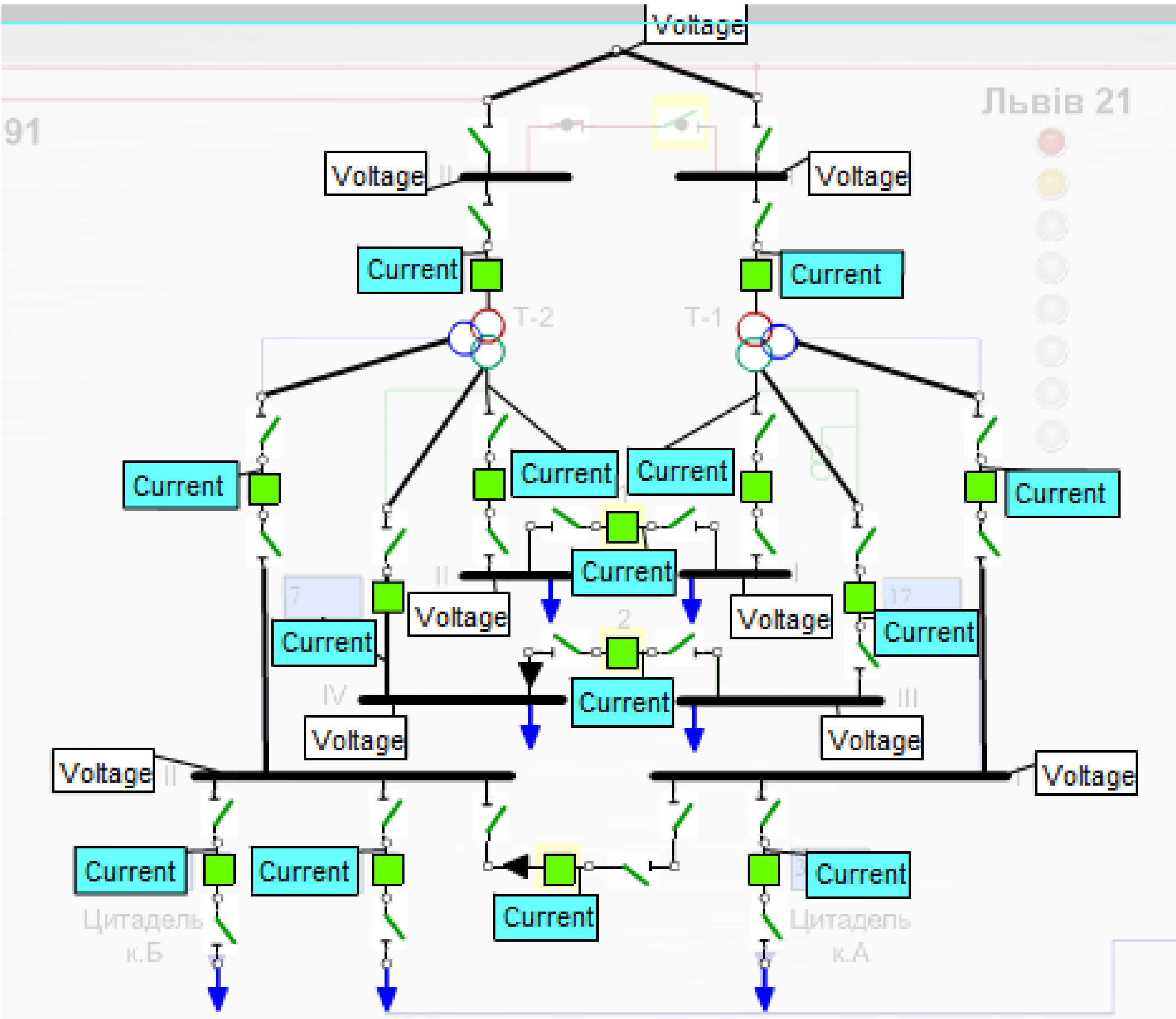

Figure 1. An example of a fragment of a mnemonic diagram of a distribution network.

2.1. Double winding and three winding transformers

When mimic diagram components were transferred from manual to automatic data preparation, the double winding transformer and three winding transformer components had a problem with assigning a number to the transformer nodes and assigning an index to the transformer branches. This issue has been fixed by adding transformer Nodes and transformer Branches inside transformer component copies. Unlike ordinary branches and nodes, transformer ones have a technological one – the transformation ratio parameter. Also, transformer branches are not visible on the mnemonic diagram, as they are located in the inner layer of the transformer [10, 11].In transformers, it is possible to set technological parameters, such as conductivity and transformation ratio [11, 12] (figure 2).

2.2. Connection

The connection component performs the function of transferring the structure parameter from node or branch copies to voltage or current output component copies. When constructing a mnemonic diagram, a copy of the connection component must be placed so that one end of the line enters the node or branch, and the other end of the line must enter the instance of the

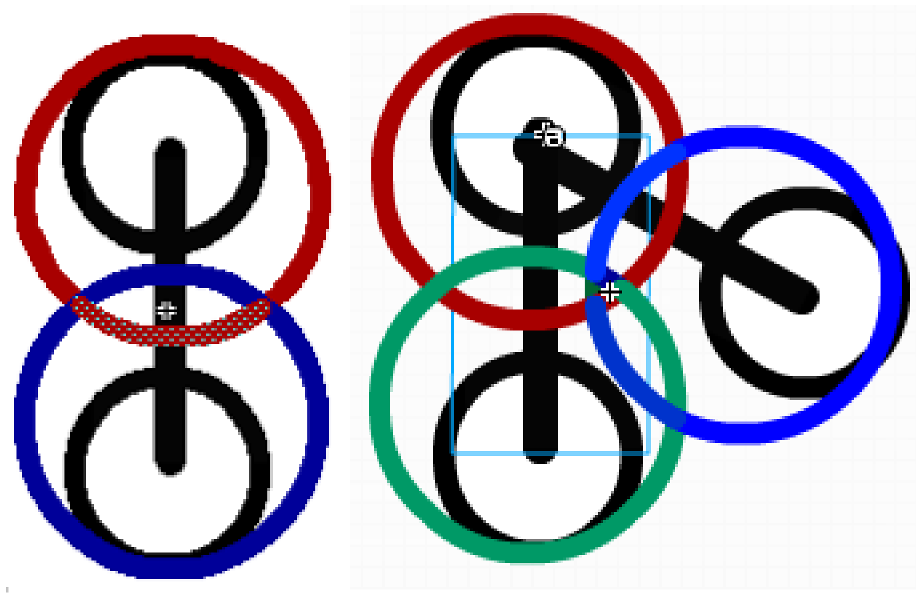

Figure 2. Inner layers of double winding and three winding transformers.

voltage or current output (figure 3) [13]. If this condition is not complete, the transfer of the structural parameter does not occur and the output will show an incorrect result (the value will be permanently equal to 0).

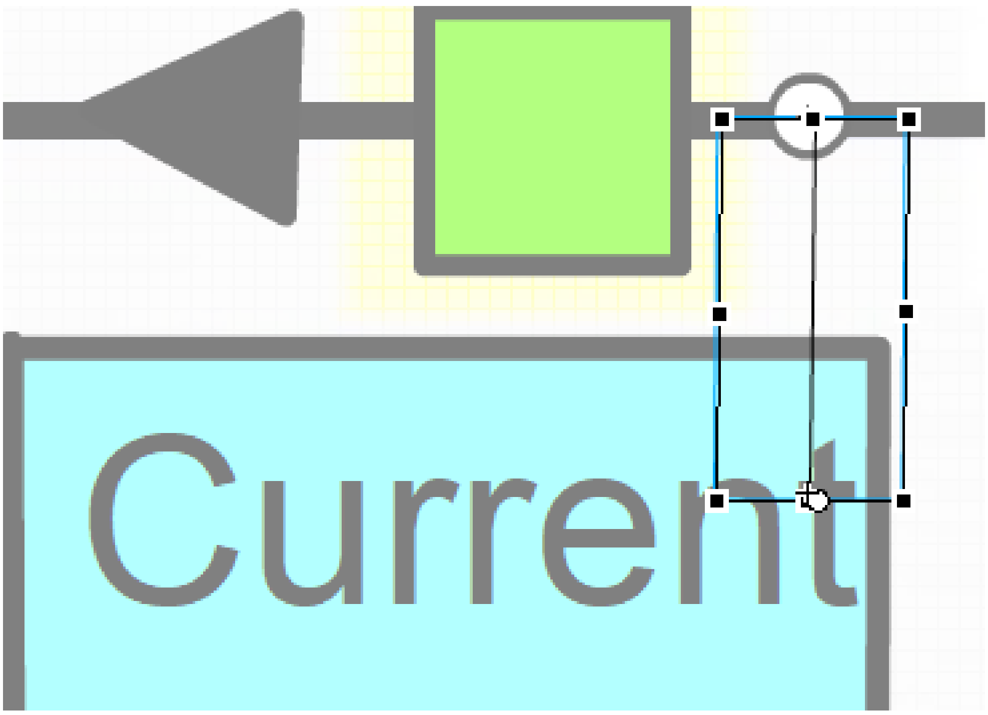

Figure 3. Visual view of the Connection component.

3. Construction of a mnemonic diagram

After getting acquainted with the modified library of components, the developer of the training task can proceed to the construction of a mnemonic diagram. This process is shown in figure 4.

A visual representation (specification) of this process and three cycles of data preparation was created using Bizagi, based on the BPMN 2.0 standard.this standard is often used to represent program process [14–16]. The following components are used from this standard [17, 18]:

- Data Object – data array
- Start Event – start of the process of constructing a mnemonic diagram
- User Task – task performed by the developer of the training task [19]
- Inclusive Gateway – gateway with condition. Depending on the fulfillment of the condition, the branching of the process depends
- End when message is send
- Start when message is received
- Sub Processes – task that contains other tasks
- Service Task – a task that is performed automatically
- End Event – completion of the mode calculation model process

The first step the developer selects from the component library is the component copies necessary to construct the mnemonic diagram. Unlike manual provisioning, in automatic, the developer does not need to set structural parameters, since the program automatically assigns structural parameters after the program starts. After adding and placing all the components on the mnemonic diagram and filling in the technological parameters for copies of the mnemonic diagram components, the program must be started. The next step is the automatic preparation of structural parameters and links. The last step is the mode calculation model, in which the value of voltages and currents is mathematically calculated. After each switching, the value of currents and voltages is recalculated [7–9, 20].

3.1. First loop through component copies

The Service task of preparing structural parameters and links consists of three cycles. In each of the cycles, structural parameters are assigned to the copies of components. Using the function of browsing all copies of the mnemonic diagram components, the process of reading the type of the mnemonic diagram component is in progress. While browsing all the components, the array of components is filled. After the array is filled, it loops over it. On the first iteration, the nodes, node buses, and transformer nodes of the mnemonic diagram are automatically assigned unique numbers and displayed on the mnemonic diagram. The switch and disconnector component copies are set to state. These components can be in two states: 1 (disabled) and 2 (active). The developer can change the state by clicking the left mouse button on the component copy (figure 5).

3.2. Second loop through component copies

In the second cycle, the component copies: capacity of node, branch, transformer branch, line, are automatically assigned structural parameters. Numbers are assigned to capacity of node, and indexes are assigned to branches, transformer branches and lines. The capacity of node number duplicates the number of the host node. The value of the index parameter depends on the numbers of nodes that are between the branch or line. Further, the structural parameters are entered into the adjacency list, and the links to the components into the link array (figure 6).

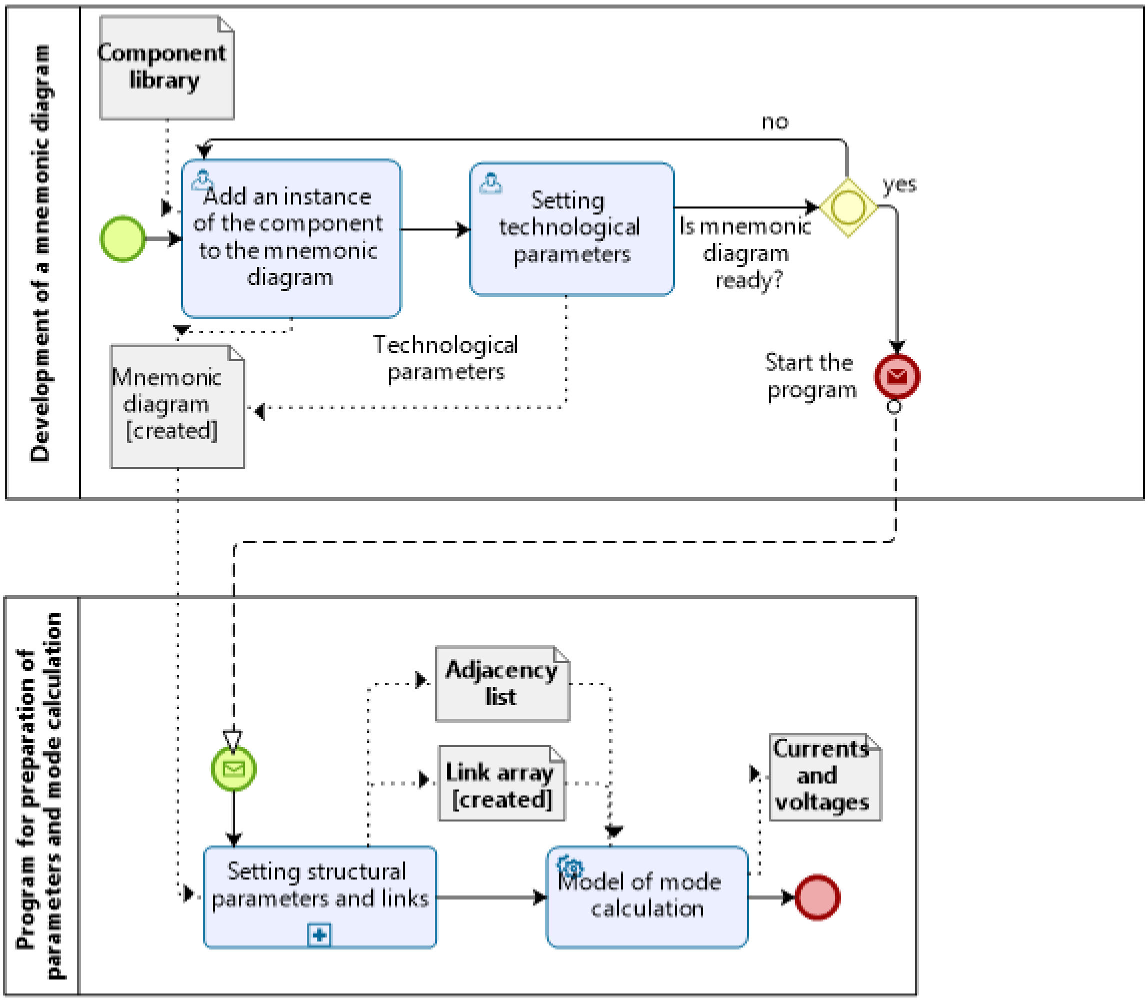

Figure 4. Visual The process of constructing a mnemonic diagram, preparing parameters, links and a mode calculation model.

3.3. Third loop through component copies

The third iteration through the component array begins by assigning indexes to the switch, disconnector, and current pointer component copies. The index of these components duplicates the index of the placement branch. The direction of the pointer is also automatically set by readout the direction of the mains current. The last process in the third cycle is the transfer of the structural parameter of the current or voltage output copies using the connection component (figure 7).

4. Conclusions

The disadvantage of the automatic method of preparing data for setting up the mode model is the increase in the time for placing component copies on the mnemonic diagram in comparison with manual preparation. This increase in time is due to the addition of a new communication component and its location on the mnemonic diagram. An error of incorrect placement of a connection component is easier to notice than an error when filling in structural parameters. The average time to fix this error is 7 seconds, but the average time to find this error is 2 seconds, and unlike the structural data filling error, there is no need to check the “Properties” menu and

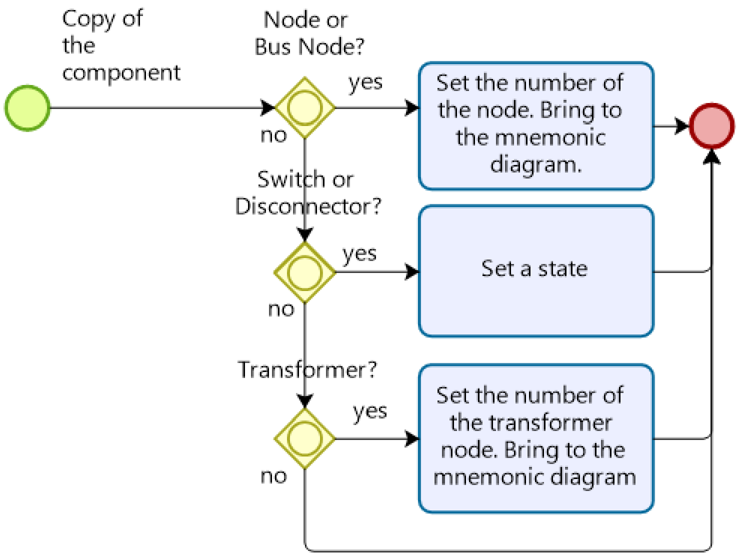

Figure 5. First loop through component copies.

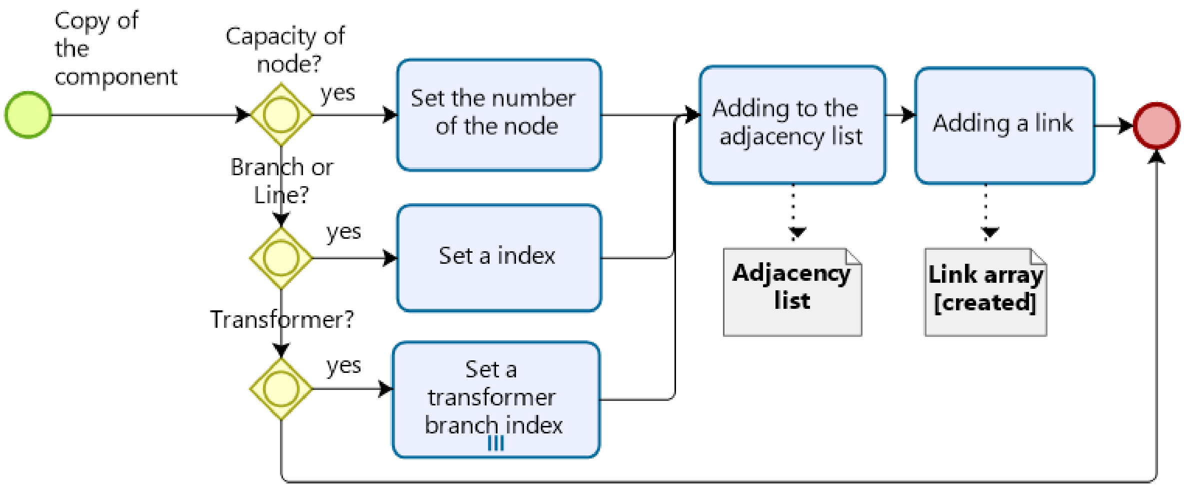

Figure 6. Second loop through component copies.

the structure parameter field for each mimic component copy. In automatic data preparation, the average time to find and correct an error is reduced by 15 minutes. The advantages of automatic data preparation are: the leveling of human error during the filling of structural parameters and the reduction of the development time of the training task. The average time to fill in the structural parameters per copy of component is 8 seconds. Depending on the number of component copies, the time to create a training session is reduced from 10 minutes to one hour. Automatic method of preparation of data for setting the model can be improved by reducing the number of cycles that go through all copies of the mnemonic diagram model. The number of cycles can be reduced to one, which will reduce the amount of computer resources needed to run the model.

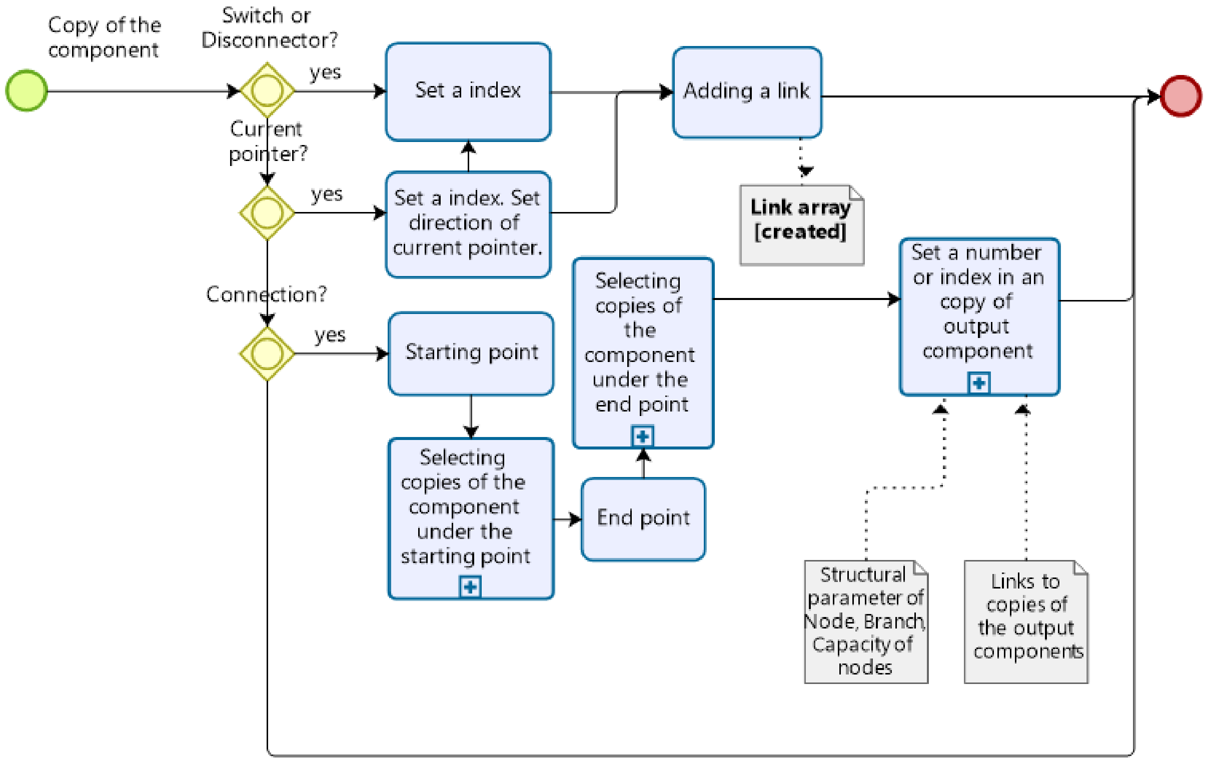

Figure 7. Third loop through component copies.

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References

[1] Li Z, Huang Y, Li L, Fu J and Wang X 2023 *Dianli Jianshe/Electric Power Construction* **44**(3) 36–48 URL `https://doi.org/10.12204/j.issn.1000-7229.2023.03.004`
[2] Liu K, Zhang C, Chen W and Zhao J 2023 *Energy Reports* **9** 37–45 ISSN 2352-4847 2022 9th International Conference on Power and Energy Systems Engineering URL `https://doi.org/10.1016/j.egyr.2022.10.362`
[3] Yang Y, Wang Y, Wang C, Zhang Y and Zhang C 2022 *Sustainability* **14**(17) 10721 ISSN 2071-1050 URL `https://doi.org/10.3390/su141710721`
[4] Lei Y, Liang Z and Ruan P 2023 *Energy Reports* **9** 785–792 ISSN 2352-4847 URL `https://doi.org/10.1016/j.egyr.2022.12.019`
[5] Zhang W, Zhang H and Zhi N 2023 *Energy Reports* **9** 683–691 ISSN 2352-4847 2022 2nd International Joint Conference on Energy and Environmental Engineering URL `https://doi.org/10.1016/j.egyr.2023.03.060`
[6] Xing Q, Chen Z, Zhang T, Li X and Sun K 2023 *International Journal of Electrical Power & Energy Systems* **145** 108637 ISSN 0142-0615 URL `https://doi.org/10.1016/j.ijepes.2022.108637`
[7] Rozegnał B, Albrechtowicz P, Mamcarz D, Rerak M and Skaza M 2021 *Energies* **14**(5) 1374 ISSN 1996-1073 URL `https://doi.org/10.3390/en14051374`
[8] Zhang T, Yu L, Yue D, Dou C, Xie X and Chen L 2023 *International Journal of Electrical Power & Energy Systems* **149** 108995 ISSN 0142-0615 URL `https://doi.org/10.1016/j.ijepes.2023.108995`
[9] gang Tan M, Zhang C, Zhang R and Chen B 2023 *International Journal of Electrical Power & Energy Systems* **145** 108675 ISSN 0142-0615 URL `https://doi.org/10.1016/j.ijepes.2022.108675`
[10] Korotkevich M A 1999 *Basics of the operation of electrical networks* (Minsk: Vysheishaia shkola)
[11] Hasheminejad S 2022 *Electric Power Systems Research* **209** 108032 ISSN 0378-7796 URL `https://doi.org/10.1016/j.epsr.2022.108032`

[12] Albrechtowicz P 2023 *Electric Power Systems Research* **220** 109266 ISSN 0378-7796 URL https://doi.org/10.1016/j.epsr.2023.109266

[13] Liepatiev A 2021 Output of current and voltage values on a mnemonic diagram during automatic preparation of mode model data *Collection of abstracts of the XXXIX Scientific and Technical Conference of Young Scientists and Specialists of the Institute of Modeling Problems in the Energy Sector. Kyiv. May 12. 2021* (Kyiv, Ukraine: G.E. Pukhov Institute for Modelling in Energy Engineering) pp 130–131 URL https://ipme.kiev.ua/wp-content/uploads/2021/05/%D0%97%D0%B1%D1%96%D1%80%D0%BD%D0%B8%D0%BA-%D1%82%D0%B5%D0%B7-%D0%BA%D0%BE%D0%BD%D1%84%D0%B5%D1%80%D0%B5%D0%BD%D1%86%D1%96%D1%97-%D0%BF%D1%80%D0%BE%D0%B5%D0%BA%D1%82-20210511.pdf

[14] Balva A O, Samoilov V D and Abramovych R P 2018 *Modeliuvannia ta informatsiini tekhnolohii* **85** 45–52 URL http://nbuv.gov.ua/UJRN/Mtit_2018_85_9

[15] Corradini F, Pettinari S, Re B, Rossi L and Tiezzi F 2023 *Robotics and Autonomous Systems* **160** 104322 ISSN 0921-8890 URL https://doi.org/10.1016/j.robot.2022.104322

[16] Valderas P, Torres V and Serral E 2022 *Journal of Systems and Software* **184** 111139 ISSN 0164-1212 URL https://doi.org/10.1016/j.jss.2021.111139

[17] Freund J and Rücker B 2019 *Real-Life BPMN: Using BPMN 2.0 to Analyze, Improve, and Automate Processes in Your Company* 4th ed (CreateSpace Independent Publishing Platform) URL https://www.infomath-bib.de/tmp/data2/Real-Life%20BPMN%20-%20edition%204.pdf

[18] Wang X, Qiao X and Zhou X 2023 *Energy Reports* **9** 2525–2537 ISSN 2352-4847 URL https://doi.org/10.1016/j.egyr.2023.01.101

[19] Smetana S I 1985 *Automated system for building simulators for dispatchers of electric networks* Dis. ... cand. tech. sciences: 05.14.02 – Electric stations, networks and systems Kiev

[20] Gaisarov R V, Akulov P A, Kondratiev E V and Latyshev A S 2005 *Energy* 47–48

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Power consumption control of multi-pump systems of the main water drainage in underground mines based on the Mamdani fuzzy inference system

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Abstract. The article considers synthesis of an expert system for controlling electric power consumption by pumps of main water drainage facilities of an underground mine on the basis of the Mamdani fuzzy inference algorithm. The proposed system has a MISO-structure (multiple-input, single-output) with two input variables, such as water inflow and power cost as well as one output coordinate – power of pumping units. Two bases of fuzzy rules such as conjunction (AND) and disjunction (OR) are formed. By simulation modelling, a comparative analysis of fuzzy control systems for power consumption by water drainage facilities is carried out, as well as a system without control, when the pump performance is stabilized, during week and month periods. It is established that OR-rule based systems can reduce power costs by 1.89% during a week and by 2.28% during a month, and AND-rule based systems by 4.13%, as well as by 5.43% during week and month, respectively. At the same time, we note that the economic effect is achieved not through a decrease in power consumption, but by adjusting the operation mode of the water drainage facility, which involves ensuring maximum efficiency of groundwater drainage when the power cost is high, and minimum efficiency when it is low.

1. Introduction

Creation of the power market in Ukraine and widespread introduction of distributed generation facilities has resulted in a radical change in principles of mutual financial settlements between distribution operators and consumers due to rapid improvement of power production technologies using renewable sources. Dynamic pricing in determining power prices has provided ample opportunities to develop new algorithms for controlling power supply and consumption in power systems of various hierarchical levels. Given that the most energy-intensive objects are industrial enterprises, there are great prospects for improving energy efficiency specifically for them.

Simultaneously, the constant change in power costs requires a significant revision of principles of managing technological operations, which have traditionally remained unchanged for many years. In particular, this concerns main water drainage facilities of underground mines designated to pump groundwater from internal working spaces of enterprises engaged in underground mineral mining. Their operation is critical for creating safe working conditions for personnel, so water drainage is controlled through ensuring maximum efficiency of pumps.

At the same time, energy efficiency is improved by optimizing performance characteristics of technological units using an automated electric drive. Design features of mine water drainage, namely reservoir for accumulating mine water, make it possible to implement a different approach to controlling the system. It will involve limiting the performance of pumps and, as a result, power consumption, in certain periods of time when the power cost is high and its significant use is economically inefficient. In this case, the main limitation will involve preventing overflow of reservoirs in case of an intensive water inflow that can cause flooding of the underground mine.

The power system, regardless of its architecture and operation algorithm, aims to reduce the cost of purchasing power from an external distribution operator. Given that for enterprises power cost can vary widely during the day, it would be logical to ensure maximum power consumption during the period of the minimum power cost. However, this is not always possible to implement for consumers, because their operation is related to ensuring safe working conditions for personnel of a certain production facility, in particular, mine water drainage. If during the enterprise operation there is a significant or abnormal water inflow into the underground mine, it is required to pump water with maximum efficiency, despite high or average power costs. Therefore, the power control system of main water drainage facilities of underground mines should have two input actions: water inflow and power cost (or the cost of power generation in case of availability of sources of distributed generation). The initial coordinate is the power of electromechanical complexes of pumps that are simultaneously in operation, i.e. their total power.

2. Literature review

A number of works are devoted to controlling multi-pumping systems.

Thus, [1–7] consider various aspects of functioning of pumping systems with several pumps using both group and individual electric drives. At the same time, some works specify parameters of pumps and the hydraulic system. In particular, Arun Shankar et al [7] looks into cavitation and water hammer, and Vodovozov et al [4] – pressure. Papers [1–3, 5] are devoted to control with the optimal operating point of the system determined by pump efficiency. Additionally, practical implementation of control using industrial logic controllers is proposed. Beshta et al. [6] is worth highlighting as it directly considers the process of controlling pumps of main water drainage facilities of the underground mine. At the same time, we note that the authors focus on improving efficiency of the pumping system in terms of its performance, but the control over power consumption depending on power costs is not sufficiently considered.

Gong and Zhu [8] optimizes operation of a group of pumping stations operating in parallel, according to the criterion of minimizing losses for power consumption by the entire technological complex. Efficiency of water drainage and flows between individual units of each pumping station are considered as limitations. A multifactor optimization criterion is proposed, which takes into account power costs in a certain period of time. The authors consider a three-tariff system with differentiation by time periods. The optimization procedure includes determining the best conditions for the functioning of each individual station according to the developed criterion using a genetic algorithm, followed by their aggregation. As a result, power costs decrease for all stations. Meanwhile, on one of them, the savings amount to almost 20%. Besides, power consumption is regulated by frequent starting/stopping of individual pumps, which, as the authors themselves note, significantly affects their reliability.

Wang et al [9] deals with development of an algorithm for controlling a multi-level system for pumping water in an urban environment during heavy rains or floods using the Particle Swarm Optimization method. As optimization criteria, the number of starts/stops of pumps and duration of their operation are considered. The proposed algorithm has significantly reduced the number of pumps, so it can be used to improve the multifactor optimization system shown in [8].

Bordeașu et al [10] explores the algorithm for controlling a multi-pump irrigation system powered by a distributed generation power system, which includes a centralized electrical grid and power production facilities using renewable energy sources, in particular, photovoltaic panels. The proposed system is multi-level. The top-level subsystem determines the procedure for starting/stopping individual pumps depending on the level of filling the tanks with water and the amount of power available for consumption. Lower-level subsystems implement a smooth start and frequency regulation of the rotation speed of the electric drive of each pump. One of the indicators of assessing efficiency of the system is the hourly level of power consumption. It is compared with the periods of different power costs. As in [8], the authors consider three-zone tariffs for different time periods. At the same time, when forming the control, the power cost is not directly used as a parameter for adjusting the algorithm, but is considered because of the power available for consumption. As a result, the system does not function in the peak tariff period. Thus, such a system is impractical to use for mine water drainage for safety reasons.

The papers [11–14] consider the control of industrial and household consumers power supply, taking into account fluctuations in the power tariff during the day.

To date, the most promising control methods include those based on fuzzy logic, artificial neural networks and machine learning, which are usually classified as smart. Moreover, in problems when an object has several input variables, it is advisable to apply a fuzzy logic inference due to simplified synthesis and control algorithms implemented. On its basis, there are developed irrigation control systems [15, 16], pumping facilities powered from autonomous power plants using renewable energy sources [17–22], control systems of wind turbines electromechanical equipment [23], urban water supply [24], cascades of multi-pump systems [25], as well as the electric drive of a separate pumping unit [26].

As mentioned earlier, the power control system of main water drainage facilities of the underground mine can be represented by a MISO-structure (multiple-input, single-output) with two input (water inflow and power cost) and one output (the power of pumps) variables. Moreover, all three coordinates are subject to expert evaluation. As a result, it is advisable to develop a smart power control system for main water drainage facilities using the Mamdani fuzzy logic inference algorithm.

The research paper aims to synthesize a system for controlling power consumption levels by electromechanical equipment at main water drainage facilities based on the Mamdani fuzzy logic inference algorithm to reduce power costs of an industrial enterprise for the power supplied by an external distribution operator.

The developed fuzzy algorithm can be applied to controlling a peak pumped-storage power plant of main water drainage facilities of underground mines [27, 28].

3. General characteristics of main water drainage facilities of the underground mine as a fuzzy control object

The synthesis of a fuzzy control system for power consumption by main water drainage facilities as part of a mining enterprise can be clearly demonstrated on the example of the Kryvorizka underground mine (Kryvyi Rih). Main water drainage facilities are placed on appropriate levels and include several pumps, usually of the same type and power. On the same levels, there are additional water reservoirs, the size of which allows accumulating required volumes of mine water entering a specific level from others (deeper ones).

A 500 m water drainage level is adopted as a control object (figure 1). Given that this level is the final stage before pumping water to the surface, where water from the entire internal space of the underground mine enters, it is equipped with the largest water reservoir and consequently the most powerful pumps. As a result, it is one of the most energy-intensive consumers of water drainage and the entire underground mine as a whole. The water drainage section of the 500m level contains seven pumps of the CNS-300x600 type with a nominal power of 800 kW each.

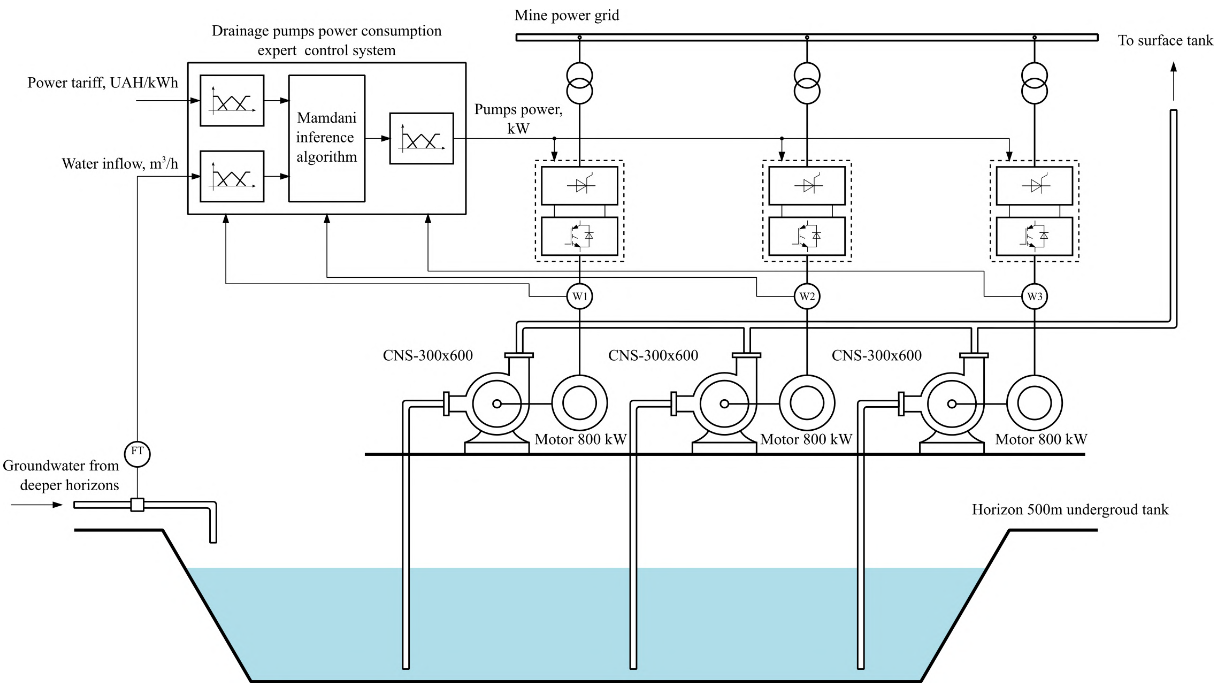

Figure 1. Water drainage facilities of the 500 meters horizon of the Kryvorizka underground mine.

Table 1. Annual groundwater inflow into the Kryvorizka underground mine for 2016-2021.

No	Year	Water inflow, m^3/year
1	2016	3281132
2	2017	3709753
3	2018	4416601
4	2019	4619121
5	2020	4784339
6	2021	4673021

Due to the reduced production volumes, compared to the design ones observed in recent years, there is a decrease in water inflow to the underground mine (table 1). This caused the need to simultaneously use only three pumps at the maximum water inflow into the working spaces and one or two under normal conditions.

After taking into account the above features during fuzzification of the fuzzy system for controlling power consumption by electrical equipment of the 500 m level, let us consider this procedure in more detail.

4. Development of a smart expert system for controlling power consumption by main water drainage facilities of the underground mine

4.1. Fuzzification of linguistic variables of a fuzzy control system

Each coordinate of the fuzzy logic inference MISO-structure, namely "water inflow", "power tariff" and "pump power" are represented by corresponding linguistic variables.

A finite set Q, used to form the membership functions of the linguistic variable "water inflow", is defined on the interval $\{q_i \in \mathbb{R} \mid q_{\min} \leq q_i \leq q_{\max}\}$, where $q_{\min}$ and $q_{\max}$ are the minimum and maximum levels of groundwater inflow into the underground mine. We assume that the linguistic variable includes three fuzzy sets: "low inflow" (Q_L), "medium inflow" (Q_M), and "high inflow" (Q_H). Membership functions to the above-mentioned fuzzy sets are formed by piecewise linear functions. This reduces computational complexity while implementing a fuzzy logic inference algorithm. The membership function for the fuzzy set "medium water inflow" is defined as triangular, for the set "high water inflow" as S-shaped, and for the set "low water inflow" as Z-shaped.

When parametrizing membership functions, the average value of water inflow over 6 years (table 1) is taken as the mean value, which is $q_m = 484.85$ m^3/h. We assume that the high water inflow exceeds 2.5 times the medium one, while the low water inflow is twice smaller, and make $q_l = 1212.13$ m^3/h and $q_h = 242.43$ m^3/h respectively. At the same time, we set the minimum value at the level of $q_{\min} = 0$ m^3/h, and the maximum value of $q_{\max} = 1500$ m^3/h.

The membership function to the fuzzy set Q_M is defined by the following expression:

$$\mu_{Q_M}(q) = f(q; q_l, q_m, q_h) = \\ = \max\left[\min\left(\frac{q - q_l}{q_m - q_l}, \frac{q_h - q}{q_h - q_m}\right), 0\right], \tag{1}$$

while:
core $(Q_M) = \{q_m\} = 484.85$ m^3/h;
supp $(Q_M) = \{q \in \mathbb{R} \mid q_l \le q \le q_h\} = 969.71$ m^3/h.

Here is an expression for determining the membership function to the fuzzy set Q_L:

$$\mu_{Q_L}(q) = f(q; q_{\min} - 1, q_{\min}, q_l, q_m) = \\ = \max\left[\min\left(\frac{q - (q_{\min} - 1)}{q_{\min} - (q_{\min} - 1)}, 1, \frac{q_m - q}{q_m - q_l}\right), 0\right], \tag{2}$$

while:
core $(Q_L) = \{q \in \mathbb{R} \mid 0 \le q \le q_l\} = 242.43 m^3/h$;
supp $(Q_L) = \{q \in \mathbb{R} \mid 0 \le q \le q_m\} = 484.85\ m^3/h$.

Here is the expression for determining the membership function to a fuzzy set Q_H:

$$\mu_{Q_H}(q) = f(q; q_m, q_h, q_{\max}, q_{\max} + 1) = \\ = \max\left[\min\left(\frac{q - q_m}{q_h - q_m}, 1, \frac{q_{\max} + 1 - q}{q_{\max} + 1 - q_{\max}}\right), 0\right], \tag{3}$$

while:
core $(Q_H) = \{q \in \mathbb{R} \mid q_h \le q \le q_{\max}\} = 287.86$ m^3/h;
supp $(Q_H) = \{q \in \mathbb{R} \mid q_m \le q \le q_{\max}\} = 1015.15$ m^3/h.

Given the membership functions to the fuzzy sets Q_L and Q_H, both the upper and lower reference values go beyond the limits of the finite set Q, that is, they increase and decrease by one respectively. This is done to avoid dividing by zero cases.

A diagram representation of membership functions to the fuzzy sets of the linguistic variable "water inflow" is shown in figure 2.

The fuzzification of the linguistic variable "power tariff" is performed on the basis of the following considerations. In compliance with the Law of Ukraine On the Electric Power Market [29] as of January 07, 2019, a new power cost system for industrial enterprises and distributors was established. This system involves the introduction of an hourly tariff mode, where power cost changes every hour depending on the market condition. What is more, one day in advance, an enterprise orders from a distributor the amount of power that is expected to

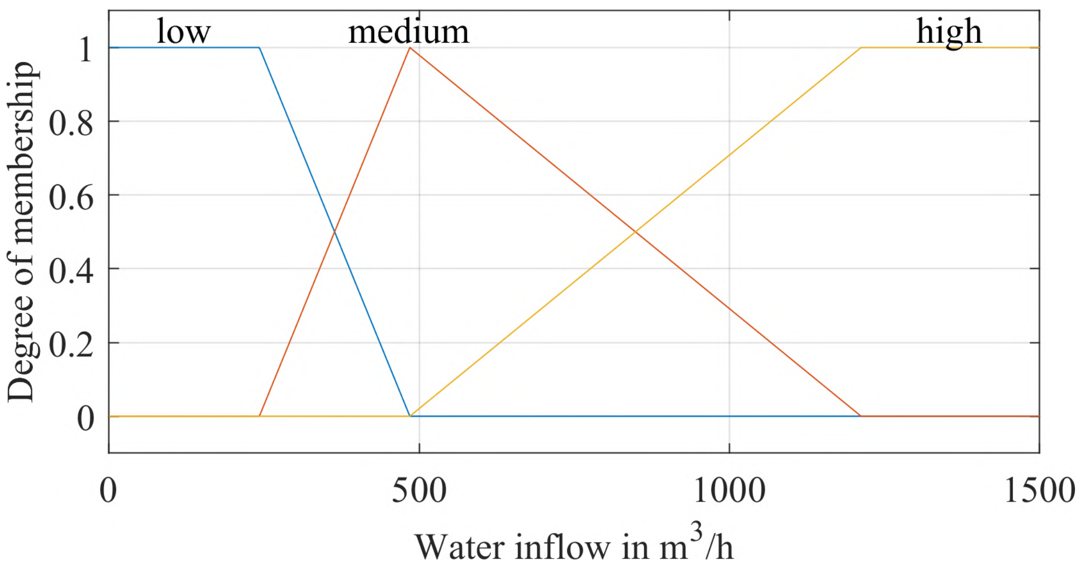

Figure 2. Membership functions to the fuzzy set "water inflow".

be consumed during each hour of the following day. This approach is fundamentally different from payments according to tariffs differentiated by time periods, which were in effect before, when the power cost was fixed. At the same time, the analysis of the hourly payment structure allows us to state that it is appropriate to distinguish three zones based on power cost, when its level is high, medium or low. Moreover, the day periods when the specified zones are virtually active coincide with peak, half-peak and night periods. This is explained by the nature of the power load schedule, namely, a high level of power consumption in morning and evening hours, a low level at night and a medium level during daylight hours. Thus, in order to formalize the fuzzy control algorithm, we differentiate the power cost in the "peak", "half-peak" and "night" zones.

As reference values for assigning membership functions for the linguistic variable "power tariff", we will use the tariff values set by the power distributor DTEK Dniprovski Elektromerezhi [30]. Also, we use the data for the case of centralized power supply and for the case of the installed distributed generation facilities. In the latter case, this variable is equivalent to the cost of power production.

For the consumers of the first voltage type, namely from 35 kV and higher, at the limit of balance distribution, which includes the Kryvorizka mine, the tariff of $c_{HP} = 0.13788$ UAH/kWh has been effective since January 01, 2022. This value will determine the power cost in the "half-peak" zone. Accordingly, the "peak" tariff is 1.5 times higher than the "half-peak" one, and the "night" tariff is 0.4 times lower. They are $c_{PK} = 0.20682$ UAH/kWh and $c_{NT} = 0.055152$ UAH/kWh respectively. These three values are used as references when forming membership functions and their further parameterizing.

The linguistic variable "power cost" is defined by a finite set on the interval $\{c \in \mathbb{R} \mid c_{\min} \leq cq \leq c_{\max}\}$, and $c_{\min} = 0$ UAH/kWh, $c_{\max} = 0.3$ UAH/kWh. Let us represent the variable as three fuzzy sets – "night zone", "half-peak zone" and "peak zone".

The membership function to the fuzzy set "night zone" is defined as Z-shaped:

$$\begin{aligned}\mu_{C_{NT}}(c) &= f(c; c_{\min}-1, c_{\min}, c_{NT}, c_{HP}) = \\ &= \max\left[\min\left(\frac{c-(c_{\min}-1)}{c_{\min}-(c_{\min}-1)}, 1, \frac{c_{HP}-c}{c_{HP}-c_{NT}}\right), 0\right],\end{aligned} \tag{4}$$

where:
$core\,(C_{NT}) = \{c \in \mathbb{R} \mid 0 \le c \le c_{NT}\} = 0.055152$ UAH/kWh;
$supp\,(C_{NT}) = \{c \in \mathbb{R} \mid 0 \le c \le c_{HP}\} = 0.13788$ UAH/kWh.
The membership function to the fuzzy set "half-peak zone" is triangular and has the following characteristics:

$$\mu_{C_{HP}}(c) = f(c; c_{NT}, c_{HP}, c_{PK}) = \\ = \max\left[\min\left(\frac{c - c_{NT}}{c_{HP} - c_{NT}}, \frac{c_{PK} - c}{c_{PK} - c_{NT}}\right), 0\right], \tag{5}$$

while:
$core\,(C_{HP}) = \{c_{HP}\} = 0.13788$ UAH/kWh;
$supp\,(C_{HP}) = \{c \in \mathbb{R} \mid c_{NT} \le c \le c_{PK}\} = 0.151668$ UAH/kWh.
The membership function to the fuzzy set "peak zone" is S-shaped and has the following characteristics:

$$\mu_{C_{PK}}(c) = f(c; c_{HP}, c_{PK}, c_{\max}, c_{\max} + 1) = \\ = \max\left[\min\left(\frac{c - c_{HP}}{c_{PK} - c_{HP}}, 1, \frac{c_{\max} + 1 - c}{c_{\max} + 1 - c_{\max}}\right), 0\right], \tag{6}$$

while:
$core\,(C_{PK}) = \{c \in \mathbb{R} \mid c_{PK} \le c \le c_{\max}\} = 0.09318$ UAH/kWh;
$supp\,(C_{PK}) = \{c \in \mathbb{R} \mid c_{HP} \le c \le c_{\max}\} = 0.16212$ UAH/kWh.
A diagram representation of membership functions to the fuzzy sets of the variable "power tariff" is in figure 3.

The output coordinate of the fuzzy power consumption control system is the total output power consumed by the drainage pumps. Moreover, it is advisable to focus on the value of this electrical parameter, and not on the number of units that are operated at a time as modern electric drives of pumps are equipped with semiconductor frequency inverters making it possible to adjust the output power of flow-generation mechanisms over a wide range.

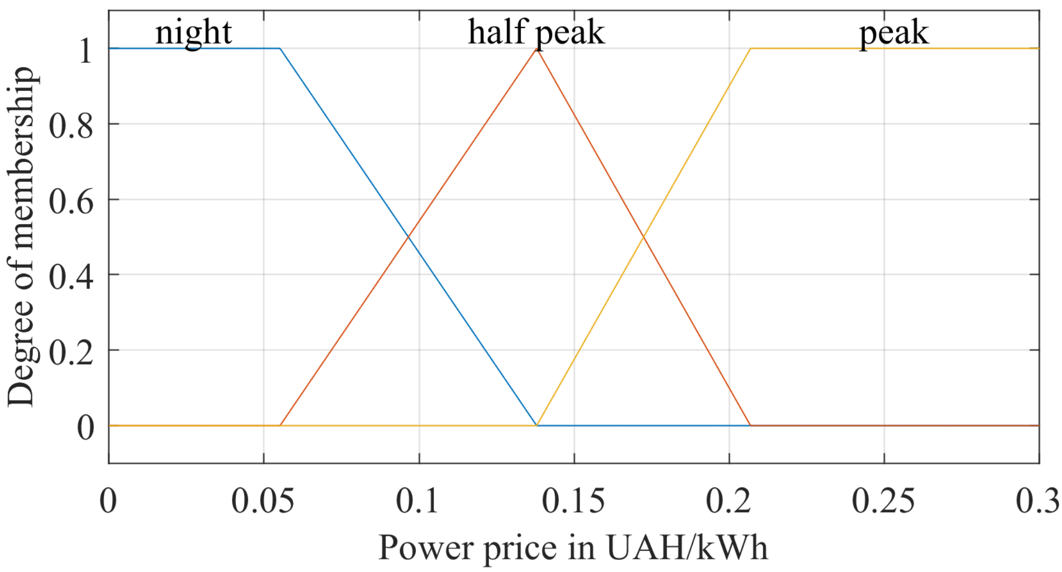

Figure 3. Membership functions to the fuzzy set "power tariff".

According to the static characteristics $P = f(Q)$ of the CNS-300x600 pump, its operating performance for the nominal angular rotation frequency of 1485 rpm is within efficiency limits of $220 - 360$ m^3/h with a power change range of $625 - 825$ kW. Taking into account the fact that one to three pumps are used for water drainage, the final set for the linguistic variable "pump power" should be determined on the interval $\{p \in \mathbb{R} \mid p_{\min} \leq p \leq p_{\max}\}$, where $p_{\min} = 625$ kW is a lower level of drainage power consumption, which corresponds to the minimum power of one CNS (centrifugal) pump $p_{\max} = 2475$ kW, i.e. when all three pumps work with the highest performance and at maximum power.

During fuzzification, we represent the linguistic variable "pump power" as three fuzzy sets corresponding to the total power consumed by one, two or three pumps. All three membership functions to the fuzzy sets are defined as triangles and the fuzzification procedure is performed.

The membership function to the fuzzy set "power of one pump" is defined by the following expression:

$$\begin{aligned} \mu_{p_{ON}}(p) &= f(p; p_{\min}, p_{nom}, p_{\max} + p_{\min}) = \\ &= \max\left[\min\left(\frac{p - p_{\min}}{p_{nom} - p_{\min}}, \frac{p_{\max} + p_{\min} - p}{p_{\max} + p_{\min} - p_{nom}}\right), 0\right], \end{aligned} \tag{7}$$

while:

$core\,(P_{ON}) = \{p_{nom}\} = 800$ kW;

$supp\,(P_{ON}) = \{p \in \mathbb{R} \mid p_{\min} \leq p \leq p_{\max} + p_{\min}\} = 825$ kW.

The peculiarity of this function is that the upper reference value is taken in such a way that one pump is supposed to work at maximum power, while the second one additionally drains water with the minimum permissible power consumption, i.e. $p_{\max} + p_{\min} = 1425$ kW.

The following membership function to the fuzzy set "power of two pumps" is formulated from the following considerations. The reference value of the lower limit is taken considering the fact that both pumps will work simultaneously at the minimum of their operating characteristics, so their power will be $2p_{\min} = 1250$ kW. The reference value of the upper limit is set assuming that two pumps will work simultaneously at the maximum working section of the static characteristics, and the third is put into operation at the minimum, i.e. $2p_{\max} + p_{\min} = 2275$ kW. As a result, the membership function is as follows:

$$\begin{aligned} \mu_{p_{TW}}(p) &= f(p; 2p_{\min}, 2p_{nom}, 2p_{\max} + p_{\min}) = \\ &= \max\left[\min\left(\frac{p - 2p_{\min}}{2p_{nom} - 2p_{\min}}, \frac{2p_{\max} + p_{\min} - p}{2p_{\max} + p_{\min} - 2p_{nom}}\right), 0\right], \end{aligned} \tag{8}$$

while:

$core\,(P_{TW}) = \{2p_{nom}\} = 1600$ kW;

$supp\,(P_{TW}) = \{p \in \mathbb{R} \mid 2p_{\min} \leq p \leq 2p_{\max} + p_{\min}\} = 1025$ kW.

Similarly, the membership function to the fuzzy set "power of three pumps" is given. At the same time, it is assumed that the reference value for the lower limit involves the operation of three pumps with the minimum power consumption of $3p_{\min} = 3 \cdot 625 = 1875$ kW, and for the upper limit – three pumps with the maximum power $3p_{\max} = 3 \cdot 825 = 2475$ kW:

$$\begin{aligned} \mu_{p_{TR}}(p) &= f(p; 3p_{\min}, 3p_{nom}, 3p_{\max}) = \\ &= \max\left[\min\left(\frac{p - 3p_{\min}}{3p_{nom} - 3p_{\min}}, \frac{3p_{\max} - p}{3p_{\max} - 3p_{nom}}\right), 0\right], \end{aligned} \tag{9}$$

while:

$core\,(P_{TR}) = \{3p_{nom}\} = 2400$ kW;

$supp\,(P_{TR}) = \{p \in \mathbb{R} \mid 3p_{\min} \leq p \leq 3p_{\max}\} = 600$ kW.

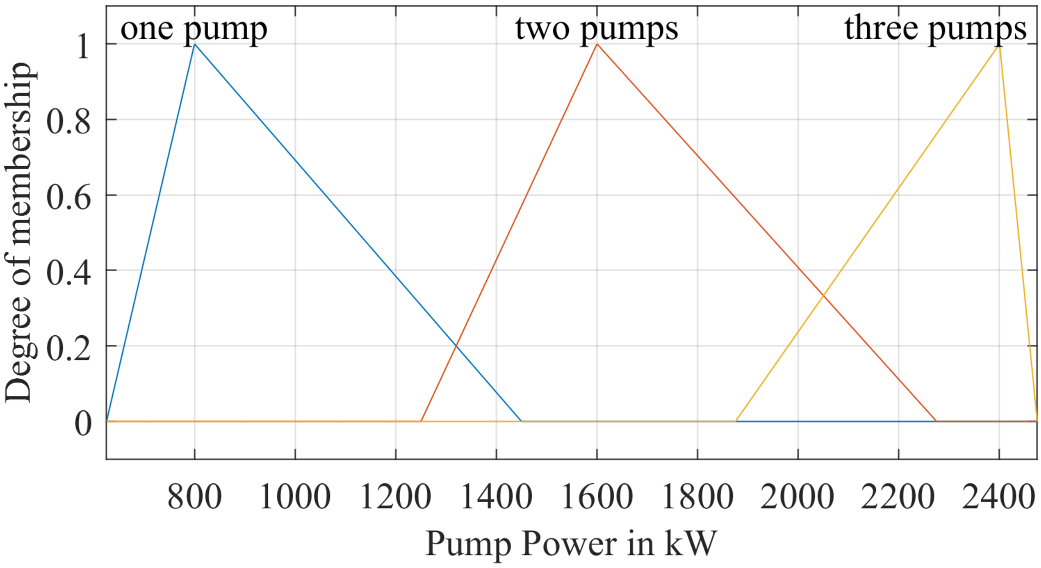

Figure 4. Membership functions to the fuzzy set "pump power".

For the first two membership functions, the upper limit includes an extra pump operation with a minimum power consumption, when intervals that do not belong to any fuzzy set defined for the linguistic variable emerge in the system of fuzzy logic inference in the domain of the finite set. For example, the upper reference value for the membership function to the fuzzy set "power of one pump" should be given at $p_{\max} = 825$ kW. However, the lower limit of the function to the fuzzy set "power of two pumps" is $2p_{\min} = 1250$ kW. As a result, the power range from 825 kW to 1250 kW does not belong to any fuzzy set, which greatly reduces control flexibility.

4.2. Synthesis of the rule base for the fuzzy inference system

On completing the fuzzification phase, it is necessary to form the rule base of the Mamdani fuzzy inference system. This procedure is carried out taking into account technological requirements for operating modes of mine water drainage. The key requirement is to ensure the efficient groundwater pumping, depending on intensity of its inflow into the underground mine. This is done to avoid flooding a shaft and mine levels, as it creates a danger to human life and makes it impossible to carry out technological operations of rock mass mining. Therefore, the highest level of significance is given to those comprising the fuzzy set "high inflow".

Since the system has two inputs, the conditional part of the base rules uses fuzzy AND conjunction operators to establish a logical relationship between the input variables of the fuzzy inference system.

Let us formalize the rules.

In all cases, if there is a high water inflow into the underground mine, all three pumps must be put into operation, regardless of the current power tariff. Moreover, the significance of this block of rules is 1, which determines the highest importance of these rules. As a result, they have the following form:

R1: **IF** $(q \text{ is } H)$ **AND** $(c \text{ is } NT)$ **THEN** p is TR;
R2: **IF** $(q \text{ is } H)$ **AND** $(c \text{ is } HP)$ **THEN** p is TR;
R3: **IF** $(q \text{ is } H)$ **AND** $(c \text{ is } PK)$ **THEN** p is TR.

Given a medium water inflow, the output power consumption of pumps depends on the current tariff. It is expedient to pump out water with maximum efficiency at the "night" tariff with all three pumps of a level, at the "half-peak" tariff with two, and at the "peak" tariff with only one. The significance of this block of rules is 0.75. As a result, the rules have the following form:

R4: **IF** (q is M) **AND** (c is NT) **THEN** p is TR;
R5: **IF** (q is M) **AND** (c is HP) **THEN** p is TW;
R6: **IF** (q is M) **AND** (c is PK) **THEN** p is ON.

Regardless of power costs, it is advisable to drain water with only one pump at low water inflow, so the following set of rules looks like this:

R7: **IF** (q is L) **AND** (c is NT) **THEN** p is ON;
R8: **IF** (q is L) **AND** (c is HP) **THEN** p is ON;
R9: **IF** (q is L) **AND** (c is PK) **THEN** p is ON.

The significance of this block of rules is 0.75 as well.

Table 2 summarizes the fuzzy rules.

Table 2. AND-type rule base of the fuzzy system controlling power consumption by water drainage facilities.

	NT	HP	PK
L	ON	ON	ON
M	TR	TW	ON
H	TR	TR	TR

The output surface of the Mamdani fuzzy inference system with nine AND rules is shown in figure 5.

For comparison, let us synthesize the rule base using the fuzzy disjunction operator OR. Water drainage facilities will consume the maximum power either at high water inflow or during the “night” tariff, and the minimum power either at low water inflow or at the “peak” tariff. Similarly, we formulate the rule for medium water inflow and the “half-peak” tariff. The resulting rule base is as follows:

R1: **IF** (q is L) **OR** (c is PK) **THEN** p is ON;
R2: **IF** (q is M) **OR** (c is HP) **THEN** p is TW;
R3: **IF** (q is H) **OR** (c is NT) **THEN** p is TR.

The first rule R1 has the significance of 1 and the other two – 0.75. It should be noted that this approach does not cover all possible combinations of value pairs of input variables.

The output surface of the Mamdani fuzzy inference system with three OR-type rules is shown in figure 6.

5. Modelling the expert system for controlling power consumption by main water drainage facilities of the underground mine

Let us analyze the efficiency of the fuzzy power consumption control system of the 500 m level. To do this, we will implement the system in MATLAB/FuzzyLogicToolbox and simulate its operation.

As a test signal for the input coordinate “water inflow”, we use a stochastic process of a random variable. The law of probability distribution is assumed to be normal with mathematical expectation $E[Q] = 500\text{m}^3/\text{h}$ and variance $\sigma^2 = D[Q] = 200\text{m}^3/\text{h}$ The state of the pseudorandom number generator is recorded by the software to ensure representativeness when comparing several control systems. Therefore, the stochastic process implementation will be conditionally constant for all experiments.

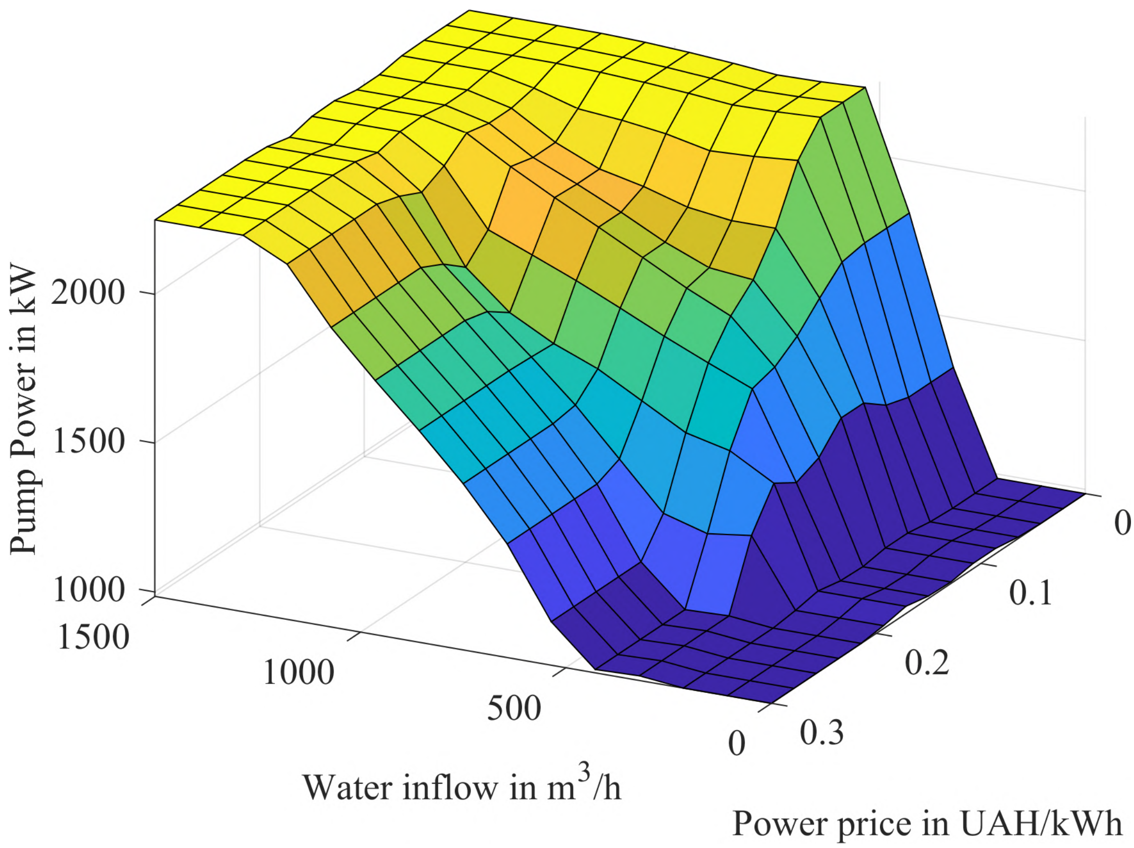

Figure 5. Output surface of fuzzy inference system.

The test signal for the input variable "power tariff" is generated by distributing tariff zones during the day. That is, the "night" zone is effective for 8 hours from 23.00 to 7.00, the "half-peak" zone – 11 hours from 7.00 to 8.00, from 11.00 to 20.00 and from 22.00 to 23.00, the "peak" zone – 5 hours from 8.00 to 11.00, from 20.00 to 22.00. To simplify, we assume that the underground mine is supplied with electric power in a centralized way by an external distributor, so the test signal has a stable periodic nature.

A comparative analysis will be performed for fuzzy logic inference systems with AND- and OR-type rule bases, as well as with a system without power consumption control, in which two

Table 3. Modelling results of power consumption fuzzy control by the water drainage facilities of the level over 7 days.

Power consumption control type	Medium power, kW	Maximum power, kW	Power consumption, kWh	Power cost, UAH
No control	1600	1600	268800	33510.36
With fuzzy inference system and OR-type rule base	1646.1	2078.18	276545.37	32878.18
With fuzzy inference system and AND-type rule base	1644.23	2243.57	276230.13	32125.55

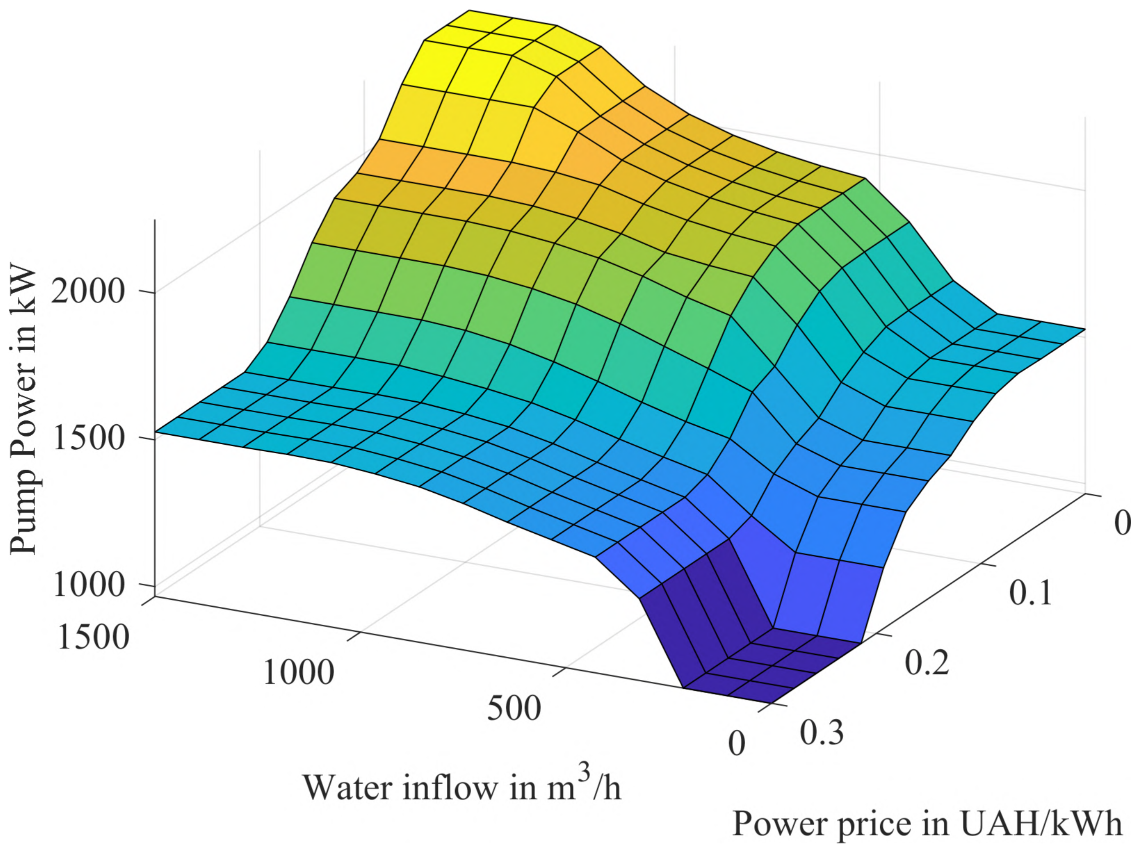

Figure 6. Output surface of fuzzy inference system.

Table 4. Modelling results of power consumption fuzzy control by the water drainage facilities of the level over 31 days.

Power consumption control type	Medium power, kW	Maximum power, kW	Power consumption, kWh	Power cost, UAH
No control	1600	1600	1190400	148403
With fuzzy inference system and OR-type rule base	1639.03	2078.18	1219441.7	145023.34
With fuzzy inference system and AND-type rule base	1623.65	2243.57	1207996.01	140344.64

pumps with nominal performance and power are simultaneously operated on the level throughout the day.

The system operation is modeled during a week and a month.

The results of the experiments are summarized in table 3 and table 4 and presented in figure 7 – 10.

The obtained results of the water drainage modelling over a week (table 3) demonstrate that when using fuzzy power consumption control systems, power costs decrease, compared to the system without such control.

The controlled system that uses the fuzzy inference algorithm with the OR-type rule base

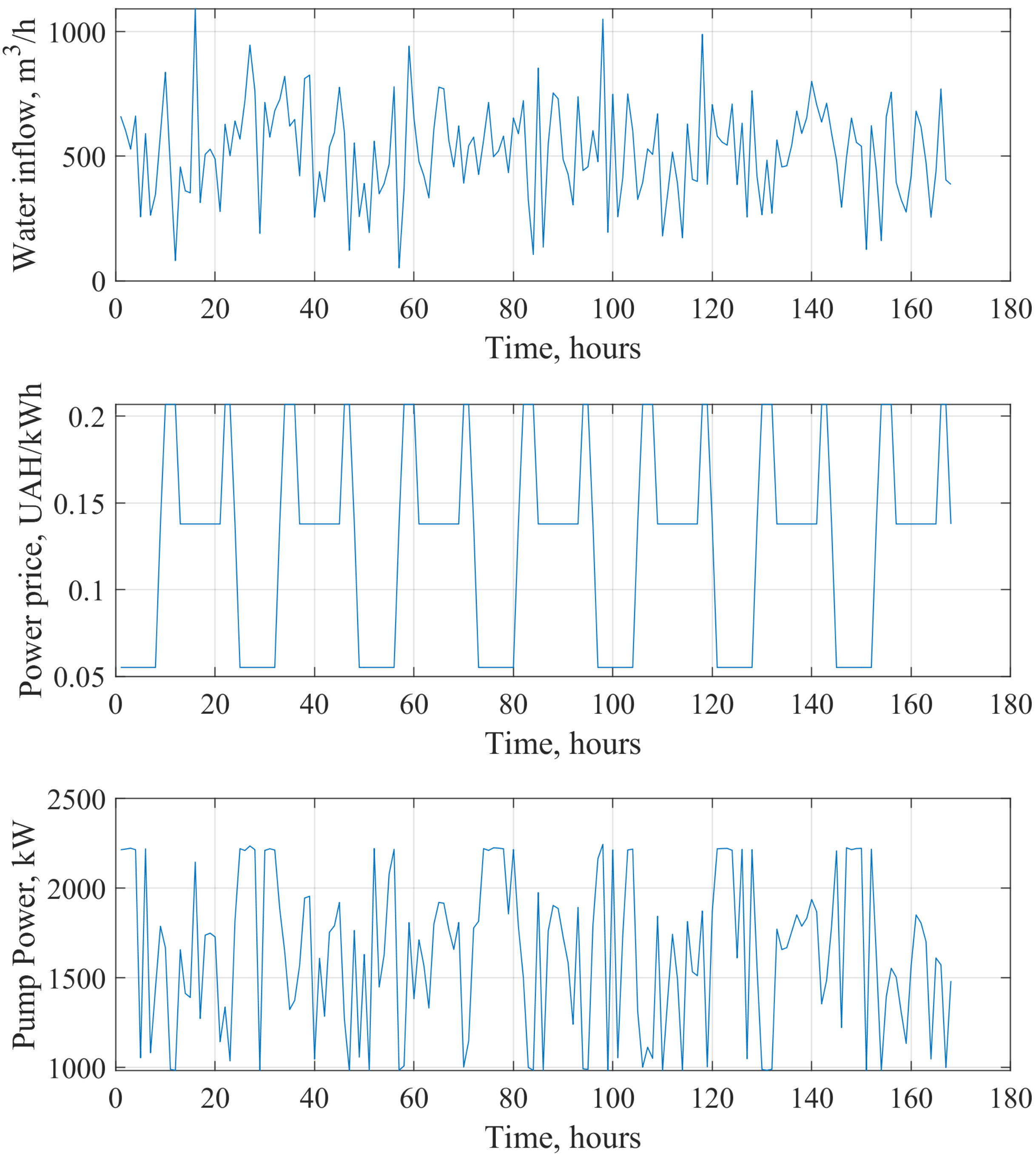

Figure 7. Results of modelling the operation of the water drainage power consumption control system based on the Mamdani fuzzy inference algorithm with the AND-type rule base over 7 days.

provides 1.89% (or UAH 632.18 in monetary value) lower level of power cost over a week than the uncontrolled one, and the use of the AND-type rule base – by 4.13% (or by UAH 1.384). If we compare smart expert systems with each other, the system with the AND-type rule base is more cost-effective. It provides 2.29% (UAH 752.63) lower power costs than the system with the OR-type rule base.

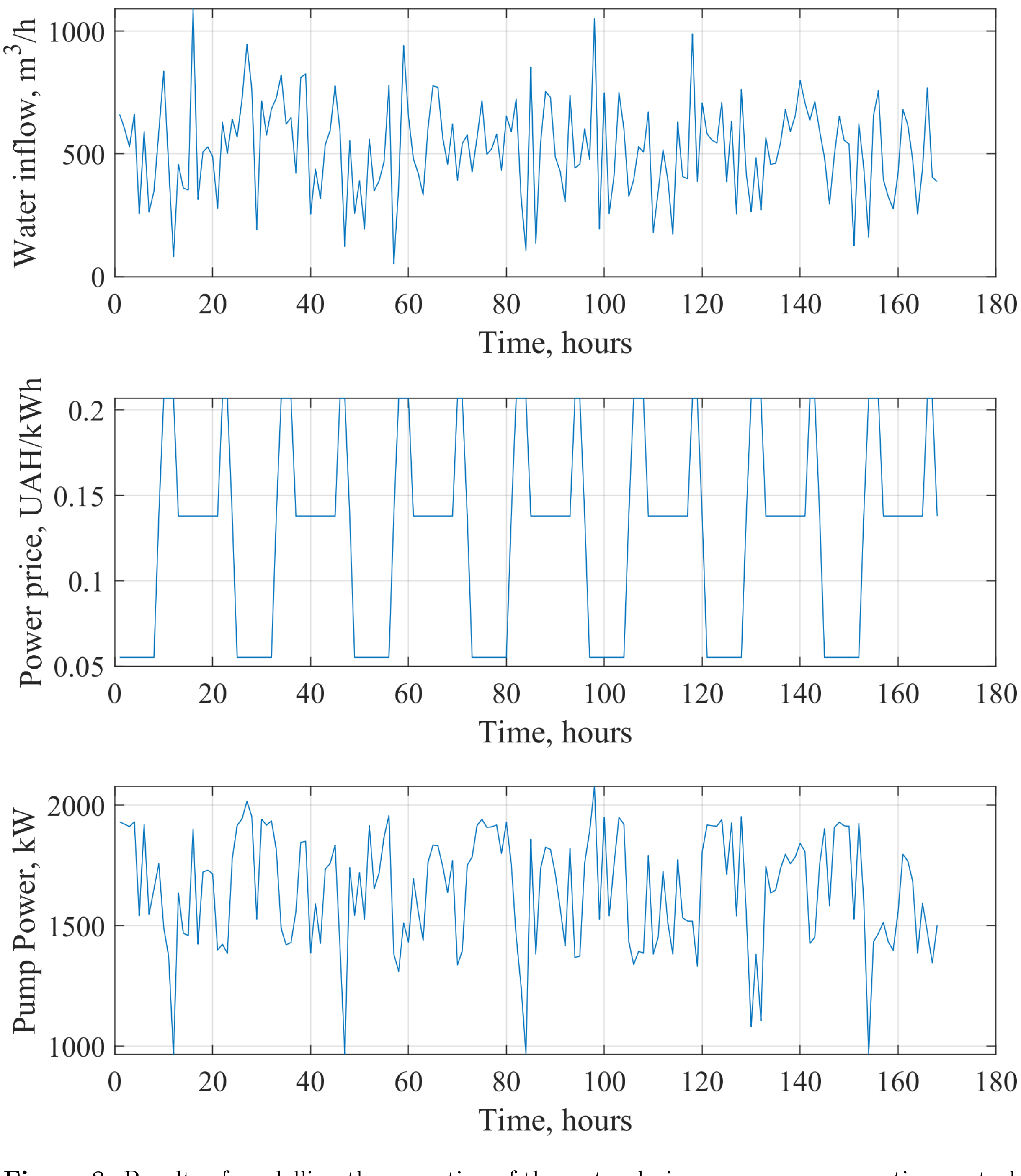

Figure 8. Results of modelling the operation of the water drainage power consumption control system based on the Mamdani fuzzy inference algorithm with the OR-type rule base over 7 days.

This trend persists if we consider a longer period, for example, a month (table 4). Moreover, the level of savings on power costs is only increasing. Thus, the fuzzy system with the OR rule base allows reducing power costs by 2.28% (by UAH 3379.66), the system with the AND-type rule base – by 5.43% (by UAH 8058.36). That is, the percentage ratio increases for both systems by 0.39% and by 1.3% compared to the week's operation. The cumulative nature of the economic effect is observed. At the same time, the AND-type rule base system provides 3.23% (or UAH

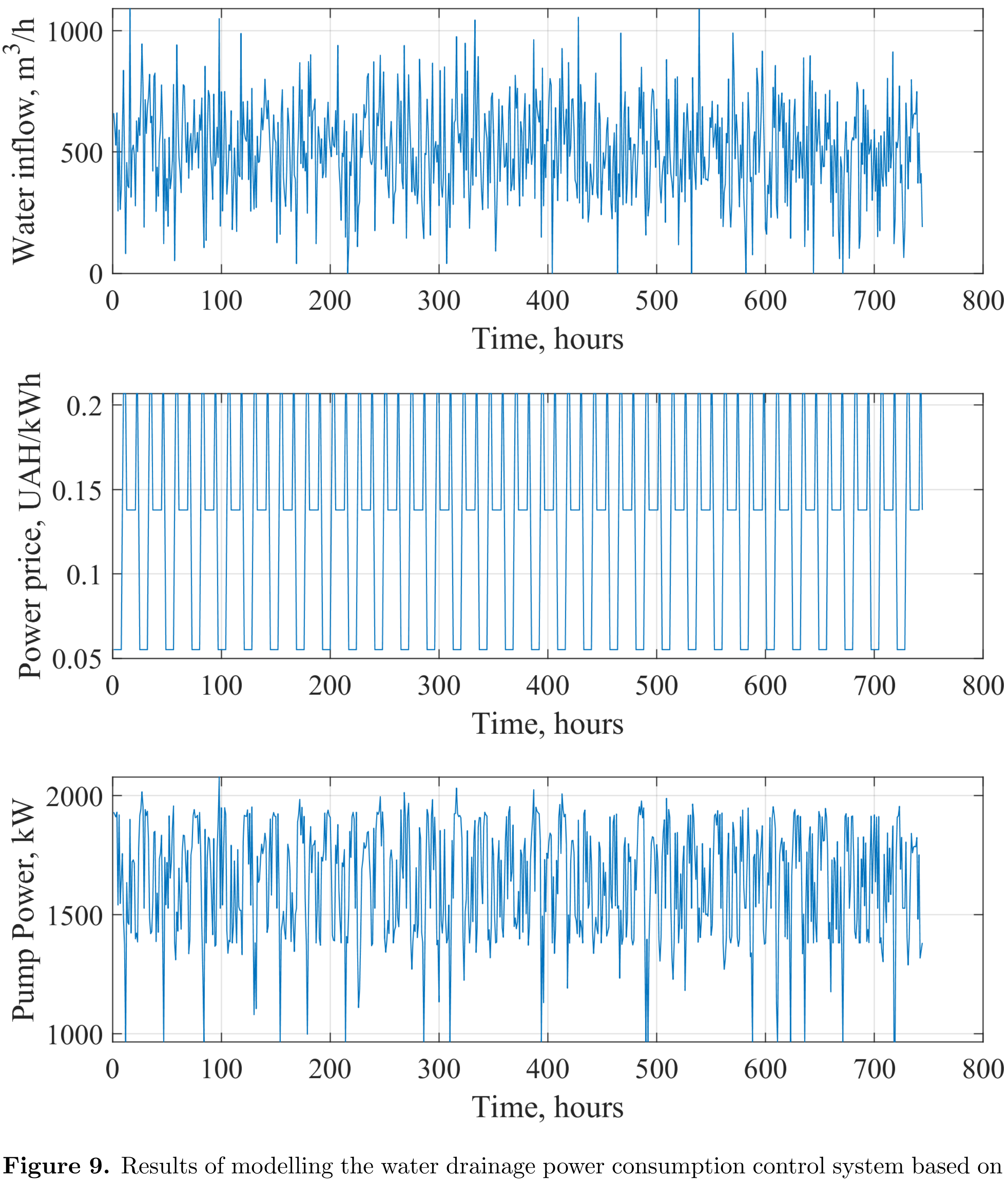

Figure 9. Results of modelling the water drainage power consumption control system based on the Mamdani fuzzy inference algorithm with the OR-type rule base over 31 days.

4,678.7) lower total cost of the produced power compared to the OR-type rule base system.

Two characteristic features of fuzzy control systems of water drainage power consumption at underground mines should be noted. The average power of the facilities at the mine level almost does not deviate from 1600 kW during the considered periods of operation. What is more, the power consumption level of uncontrolled systems is lower. This is due to the fact that in fuzzy control systems, power is consumed unevenly and there are long periods when the water inflow

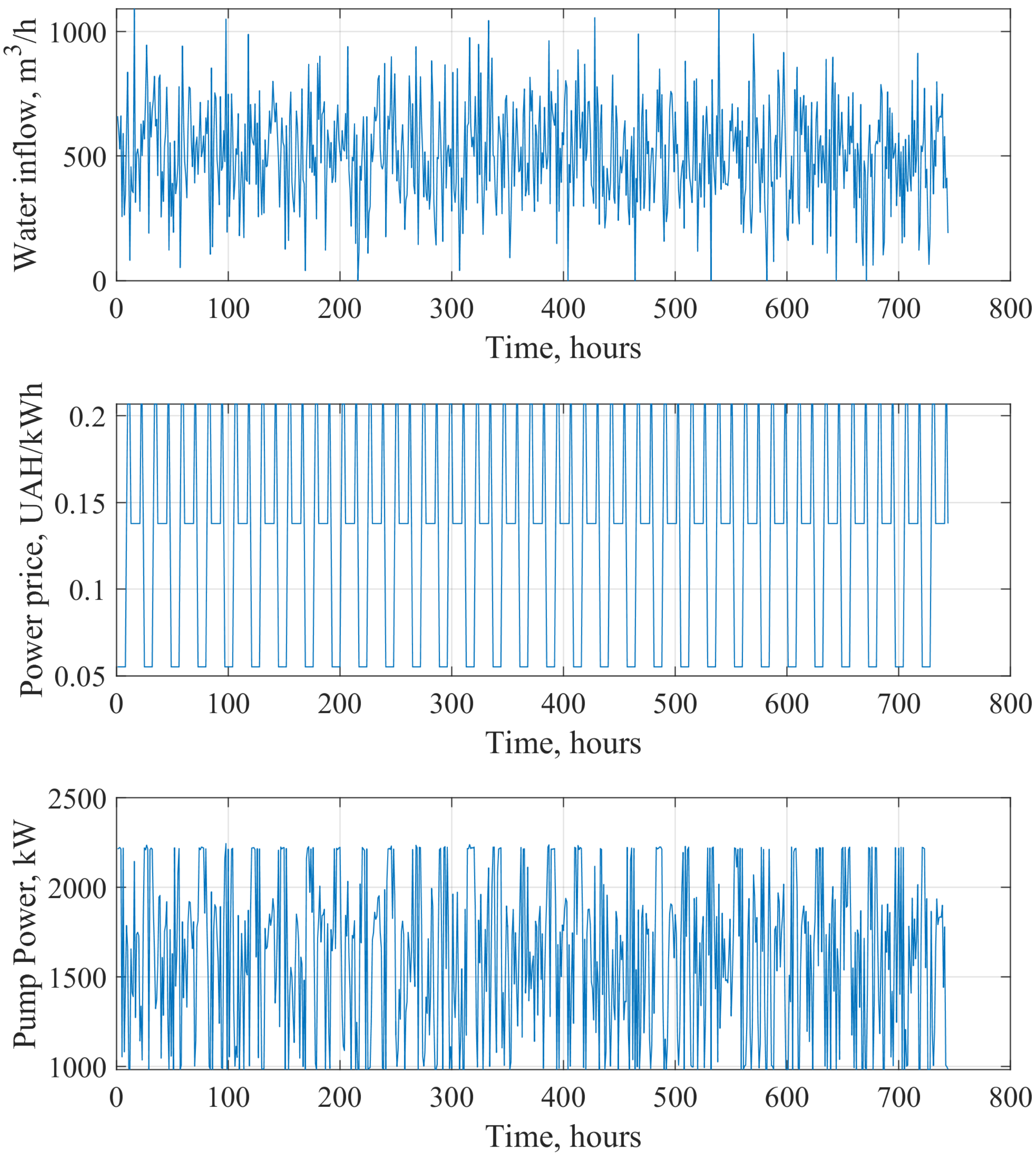

Figure 10. Results of modelling the water drainage power consumption control system based on the Mamdani fuzzy inference algorithm with the AND-type rule base over 31 days.

is high and three pumps are running at the same time, which leads to an increased level of power consumption. However, the fuzzy control algorithm allows increasing economic efficiency of the system due to the transfer of the high power consumption period to the “night” tariff time, thereby reducing the total cost of produced power.

6. Conclusions

The proposed expert control system of power consumption by main water drainage facilities of the underground mine based on the Mamdani fuzzy logic algorithm demonstrates its expected economic efficiency. Correspondingly, it is to be recommended for implementation at the relevant facility of iron ore underground mines.

The higher quality of control is demonstrated by the system with a conjunction-type fuzzy rule base. The level of power consumption in the uncontrolled system is lower due to uniformity of output power distribution by electromechanical drainage facilities during the day.

Further improvement of fuzzy control systems consists in increasing energy efficiency, i.e. reducing power consumption by main water drainage facilities of underground mines, which can be achieved by introducing an additional limitation for the power level of pumps running simultaneously during fuzzification of the corresponding linguistic variable.

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References

[1] Vodovozov V and Raud Z 2017 *IET Electric Power Applications* **11**(5) 911–917 ISSN 1751-8679 URL https://onlinelibrary.wiley.com/doi/abs/10.1049/iet-epa.2016.0361
[2] Vodovozov V, Bakman I, Raud Z and Lehtla T 2016 High-efficiency predictive control of pumping *2016 15th Biennial Baltic Electronics Conference (BEC)* pp 203–206 URL https://doi.org/10.1109/BEC.2016.7743764
[3] Bakman I and Gevorkov L 2015 Speed control strategy selection for multi-pump systems *2015 56th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON)* pp 1–4 URL https://doi.org/10.1109/RTUCON.2015.7343174
[4] Vodovozov V, Raud Z and Gevorkov L 2015 *Electrical, Control and Communication Engineering* **9**(1) 23–29 URL https://doi.org/10.1515/ecce-2015-0008
[5] Bakman I 2014 *Electrical, Control and Communication Engineering* **6**(1) 26–31 URL https://doi.org/10.2478/ecce-2014-0014
[6] Beshta A, Balakhontsev A, Khudoliy S, Khudy E and Khuda O 2012 *Scientific Reports on Resource Issues* **2** 66–75
[7] Arun Shankar V, Subramaniam U, Padmanaban S, Holm-Nielsen J B, Blaabjerg F and Paramasivam S 2019 *Energies* **12**(7) 1351 ISSN 1996-1073 URL https://doi.org/10.3390/en12071351
[8] Gong Y and Zhu B 2022 *Processes* **10**(10) 1935 ISSN 2227-9717 URL https://doi.org/10.3390/pr10101935
[9] Wang H, Lei X, Khu S T and Song L 2019 *Water* **11**(5) 1002 ISSN 2073-4441 URL https://doi.org/10.3390/w11051002
[10] Bordeașu D, Proștean O, Filip I, Drăgan F and Vașar C 2022 *Mathematics* **10**(21) 4019 URL https://doi.org/10.3390/math10214019
[11] Kinhekar N, Padhy N P and Gupta H O 2014 *International Journal of Electrical Power & Energy Systems* **55** 612–619 ISSN 0142-0615 URL https://doi.org/10.1016/j.ijepes.2013.10.011
[12] Kallel R, Boukettaya G and Krichen L 2015 *Renewable Energy* **81** 123–135 ISSN 0960-1481 URL https://doi.org/10.1016/j.renene.2015.03.024
[13] Gottwalt S, Ketter W, Block C, Collins J and Weinhardt C 2011 *Energy Policy* **39**(12) 8163–8174 ISSN 0301-4215 URL https://doi.org/10.1016/j.enpol.2011.10.016
[14] Thakur J and Chakraborty B 2016 *Energy* **114** 895–912 ISSN 0360-5442 URL https://doi.org/10.1016/j.energy.2016.08.030
[15] Dias J, Coelho J P and Gonçalves J 2015 Fuzzy control of a water pump for an agricultural plant growth system *2015 7th International Joint Conference on Computational Intelligence (IJCCI)* vol 2 pp 156–161
[16] Singh A K, Tariq T, Ahmer M F, Sharma G, Bokoro P N and Shongwe T 2022 *Energies* **15**(19) 7199 ISSN 1996-1073 URL https://doi.org/10.3390/en15197199

[17] Errouha M, Derouich A, Motahhir S, Zamzoum O, El Ouanjli N and El Ghzizal A 2019 *Energy Reports* **5** 853–865 ISSN 2352-4847 URL https://doi.org/10.1016/j.egyr.2019.07.001
[18] Hilali A, El Ouanjli N, Mahfoud S, Al-Sumaiti A S and Mossa M A 2022 *Energies* **15**(22) 8518 ISSN 1996-1073 URL https://doi.org/10.3390/en15228518
[19] Saoudi A, Krim S and Mimouni M F 2021 *Energies* **14**(24) 8245 ISSN 1996-1073 URL https://doi.org/10.3390/en14248245
[20] Yussif N, Sabry O H, Abdel-Khalik A S, Ahmed S and Mohamed A M 2021 *Energies* **14**(1) 104 ISSN 1996-1073 URL https://doi.org/10.3390/en14010104
[21] Bellahirich S, Mezghani D and Mami A 2021 *Energies* **14**(17) 5217 ISSN 1996-1073 URL https://doi.org/10.3390/en14175217
[22] Ledesma J R, Almeida R H and Narvarte L 2022 *Sustainability* **14**(15) 9318 ISSN 2071-1050 URL https://doi.org/10.3390/su14159318
[23] Uskov A, Shchokin V, Mykhailenko O and Kryvenko O 2020 *E3S Web of Conferences* **166** 04006 ISSN 2267-1242 URL https://doi.org/10.1051/e3sconf/202016604006
[24] Studziński J and Ziółkowski A 2020 *Entropy* **22**(9) 1014 ISSN 1099-4300 URL https://doi.org/10.3390/e22091014
[25] Baranidharan M and Singh R R 2022 *Energies* **15**(12) 4343 ISSN 1996-1073 URL https://doi.org/10.3390/en15124343
[26] Suwongsa T, Areerak K, Areerak K and Pakdeeto J 2021 *Energies* **14**(11) 3330 ISSN 1996-1073 URL https://doi.org/10.3390/en14113330
[27] Mykhailenko O and Budnikov K 2022 *IOP Conference Series: Earth and Environmental Science* **1049**(1) 012055 ISSN 1755-1315 URL https://doi.org/10.1088/1755-1315/1049/1/012055
[28] Sinchuk I, Mykhailenko O, Kupin A, Ilchenko O, Budnikov K and Baranovskyi V 2022 Developing the algorithm for the smart control system of distributed power generation of water drainage complexes at iron ore underground mines *2022 IEEE 8th International Conference on Energy Smart Systems (ESS)* pp 116–122 URL https://doi.org/10.1109/ESS57819.2022.9969263
[29] Verkhovna Rada of Ukraine 2017 Law of Ukraine “On Electricity Market” URL https://zakon.rada.gov.ua/laws/show/2019-19?lang=en#Text
[30] DTEK Dniprovski Elektromerezhi 2023 Tariffs for power distribution services URL https://www.dtek-dnem.com.ua/ua/services-tariffs

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Studying the interaction process of a solid particles flow with the hydraulic classifier flowing part

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Studying the interaction process of a solid particles flow with the hydraulic classifier flowing part

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Abstract. The paper provides a theoretical description of the solid particles movement process along with the horizontal flow of slurry within the hydraulic classifier flow part. Three modes of movement of solid particles are described: deceleration relative to the slurry flow at a constant speed or its increase, acceleration relative to the slurry flow at a decrease in its speed, with the speed of the slurry flow. The complex equation of solid particles motion in a horizontal co-flow of liquid. A graphic description of the process is given. A laboratory installation was developed to study the interaction of the hydraulic classifier flow part with the slurry flow. Experimental studies were carried out and quantitative process parameters were determined during the movement of rolled quartz solid particles in the size range < 1.8 mm and < 0.2 mm. For the first time in crisis economic conditions, in order to confirm the reliability of previously obtained analytical dependencies to determine the rational parameters of hydraulic disintegrators and determine the operational characteristics of equipment, full-scale experimental studies of the JPD 300-120 suction dredger equipped with an innovative ejector soil suction head with a jet disintegrator system were carried out.

1. Introduction

The processing of fine-grained materials is traditionally carried out in gravitational apparatus with a horizontal movement of the carrier flow: horizontal classifiers, deslimators, screw classifiers, decanters, horizontal settling tanks, etc. [1]

Despite the mass nature of the work aimed at studying the process of falling solid particles in a stationary liquid, the process of motion of solid particles relative to a moving horizontal flow of a carrier slurry remains practically unexplored. Unprovenly considered that in a carrier horizontal flow solid particles move with a flow velocity [2].

It is known that the rational size for gravitational processing, for example, quartz particles, is $0.15 < d < 5$ mm. In this case, the separation range for horizontal classifiers can be considered the fineness $0.1 < d < 0.2$ mm [3].

Thus, to justify the rational parameters of the apparatus for the gravitational processing of granular materials in a horizontal flow, it is sufficient to simulate the movement of solid particles which have a size withing the separation range expected values [4, 5].

2. Methodology

The work used a complex research method. A theoretical study of the interaction process between the hydraulic classifier flow part and the flow of solid particles that move along with the horizontal flow of the slurry is made in the form of physical and mathematical modeling. The process of co-movement of solid particles and slurry is described using the Lagrange method.

Experimental study of the process was carried out on the developed laboratory installation [6, 7]. Processing and analysis of experimental data were performed using the methods of mathematical statistics and planning of experiments, and the approximating dependences were obtained by the least squares method. Measurements of technological and design parameters were carried out using standard metric equipment.

3. Results and discussion

3.1. A theoretical study

The characteristic modes of movement of solid particles in a horizontal slurry flow during hydraulic classification in a horizontal flow are:

- movement of particles with deceleration relative to the carrier flow at a constant and increasing speed of its movement;
- movement of particles with acceleration relative to the carrier flow with a decrease in the speed of its movement;
- movement of particles with the speed of the carrier flow.

To describe the process of interaction of the horizontal hydraulic classifier flow part with a slurry flow that includes suspended solid particles moving along, we apply the Lagrange method. Let a solid particle move under the action of a horizontal fluid flow along it (figure 1). The horizontal projection of the velocity vector of a solid particle is directed along the motion of the liquid. The horizontal motion of a solid particle is characterized by its mass in a liquid m, force of the hydrodynamic pressure F_{av} at the velocity of the carrier flow U_x and resistance force P, at the speed of movement of a solid particle relative to the carrier flow v_x (figure 1).

$$m\frac{U_x}{dt} = F_{av} - P \tag{1}$$

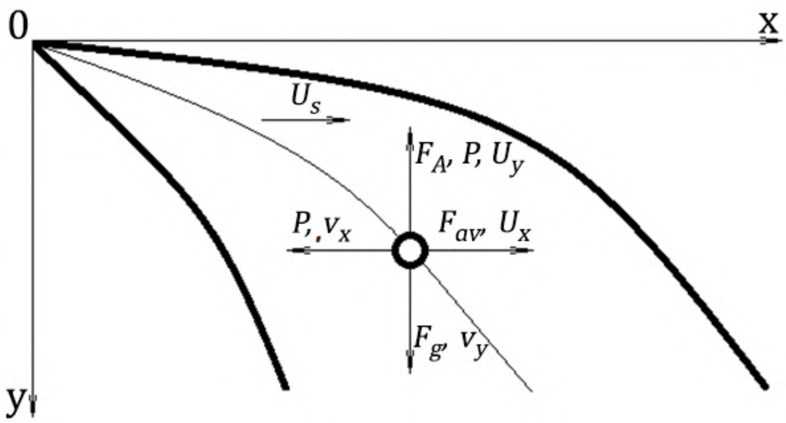


Figure 1. Scheme of the process of a solid particle motion in a horizontal liquid flow.

After transformations, the equation of motion of a solid particle in a horizontal liquid flow will take the form

$$U_x^p = \left(\frac{3}{4} \cdot \frac{\rho_s}{\rho_q - \rho_s} \cdot \frac{C_f}{d_g}\right) \int (U_x^2 - v_x^2)dt + C. \tag{2}$$

The integration constant C is defined as the initial velocity of the solid particle U_{x0}^p.

Let us analyze the obtained dependence and consider three modes of motion of a solid particle relative to the carrier flow.

Let the solid particle be motionless, that is $U_x^p = 0$. In this case, the velocity of the liquid relative to the solid particle U_x is equal to the velocity of the solid particle relative v_x

$$U_x = v_x. \tag{3}$$

The connected movement of a solid particle and a carrier flow can occur in the range $U_x > v_x \geq 0$, in this case, the equation of motion (2) takes the form

$$\begin{gathered}U_x^p = \left(\frac{3}{4}\cdot\frac{\rho_s}{\rho_q-\rho_s}\cdot\frac{C_f}{d_g}\right)\int(U_x^2 - v_x^2)dt + C \qquad \text{if } U_x^p < U_x,\\ U_x^p = \left(\frac{3}{4}\cdot\frac{\rho_s}{\rho_q-\rho_s}\cdot\frac{C_f}{d_g}\right)\int(U_x^2 + v_x^2)dt + C \qquad \text{if } U_x^p > U_x,\\ U_x^p = \left(\frac{3}{4}\cdot\frac{\rho_s}{\rho_q-\rho_s}\cdot\frac{C_f}{d_g}\right)\int(U_x^2)dt + C \qquad \text{if } U_x^p = U_x, v_x = 0.\end{gathered} \tag{4}$$

The counter motion of a solid particle and a carrier flow is characterized by the mode of motion $U_x < v_x$, while the equation of motion will retain the form (2).

Graphical representation of this process, in the absence of relative motion of the carrier flow and solid particles in the original cut, that is $U_{x0}^p = U_{x0}$, $v_{x0} = 0$ shown in the figure 2.

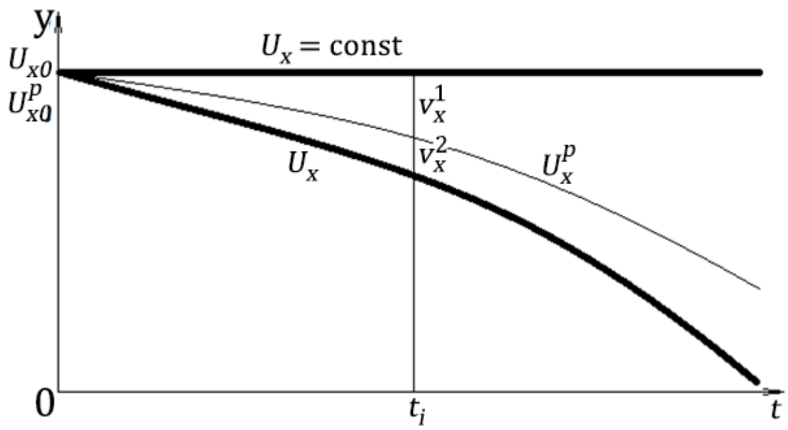


Figure 2. Scheme of the process of co-movement of a solid particle and a horizontal liquid flow.

Process analysis shows that within time t the function U_x^p is limited by the functions $U_x = const$ and U_x. The speed of a solid particle movement, in the i-th section, relative to the carrier horizontal flow, moving at a constant velocity, is taken as v_{xi}^1, but with relation to the decelerating flow v_{xi}^2 (figure 2).

The graphical representation of this process is built on the basis of the following hypothesis. Carrier flow moves in laminar mode. At a time interval t, at a constant velocity of the carrier flow a solid particle can move with relative deceleration, that is $U_x = const \geq U_{xi}^p$. When the carrier flow slows down, the solid particle can move with relative acceleration, $U_{xi}^p \geq U_{xi}$. That is, the particle velocity function is within $U_x = const \geq U_{xi}^p \geq U_{xi}$.

The theoretical substantiation of the process of relative movement of solid particles and the carrier horizontal flow is very difficult. A rational and more informative method of modeling the process, in a narrow designated area, can be considered an experimental study, which will allow to determine the values of relative velocities v_{xi}^1, v_{xi}^2.

One of the important factors influencing the process of relative motion of a solid particle in an carrier flow is the particle form. However, in the designated area of motion velocities and size particles, characterized by the number Re, there is a mode of motion of a solid particle close to laminar, at which, in accordance with the data of [6], the form of the particle has an insignificant effect on its motion.

The vertical projection of the particle velocity vector is characterized by the sediment process, and is determined by the absolute value of the particle weight in the liquid and the resistance force in liquid, directed in the direction opposite to the direction of movement (figure 1).

$$F_g - F_A = P$$

where F_g – gravity, H; F_A – strength of Archimedes, H; P – resistance force, H.

Due to the traditional nature of the use of raw materials with a high content of rounded quartz particles (construction and glass sands), the investigated area of fineness $0.15 < d < 5$ mm turned out to be the most studied experimentally. The literature sources provide data from different authors who obtained experimental values of the velocity of free fall of quartz particles [8]. Thus, in view of the presence of a sufficient amount of experimental material, in further studies, the final velocity of the fall of quartz particles will be taken according to the experimental data known in the literature. It should also be noted that at the indicated velocities of the carrier flow, the sedimentation process time is much longer than the time of unsteady motion of a solid particle, so this factor is not taken into account in the model.

When taking into account the relative displacement of a solid particle driven by a horizontal carrier flow in the horizontal and vertical directions, the formula for constructing the particle trajectory will take the form

$$x = \int \frac{U_x \pm v_x}{U_y - v_y} dy + C.$$

Let us replace the parameter that takes into account the relative vertical displacement by the experimental value of the falling velocity of a solid particle in water $U_y - v_y = \omega$ then

$$x = \int \frac{U_x \pm v_x}{\omega} dy + C.$$

where ω is experimental value of the speed of free fall of a solid particle, m/s.

The integration constant C characterizes the initial conditions for the motion of a solid particle, and, when the origin of coordinates is located in the initial position of the solid particle, the constant $C = 0$.

Let us assume that the movement of a liquid and a solid particle proceeds without mutual displacement, that is $v_x = 0$. Thus, we simplify the consideration of the process and equate the horizontal projection of the velocity of a solid particle and the velocity of a liquid $U_p^x = U_x$. Then the equation of motion of a solid particle under the action of a horizontal flow takes the form

$$x = \int \frac{U_x}{\omega} dy + C.$$

and after integration

$$x = \frac{U_x}{\omega} y \tag{5}$$

3.2. Experimental studies

Laboratory studies of the interaction process of the horizontal hydraulic classifier flow part with a pulp flow that includes suspended solid particles are performed on the basis of specialized laboratory equipment. Laboratory equipment for studying the processes of gravitational processing of granular materials is based on the use of a horizontal multi-section classifier HMC. With the use of the HMC classifier, fundamental laboratory studies were carried out to study the movement of granular material particles in a horizontal carrier flow. Laboratory installation based on the HMC classifier, consists of a horizontal multi-section classifier 1, a jet feeder 2, a water supply system (figure 3).

The horizontal multi-section classifier is an elongated vessel of rectangular section 1, in the lower part divided into 12 compartments 3, equipped with discharge nozzles 4. Power is supplied through the intake pipe 5, the sludge is drained through the drain pipe 6.

The jet feeder 2 is designed to prepare the slurry of specified parameters and feed it into the inlet pipe 5 of the horizontal multi-section classifier 1.

Preparation of the slurry in the jet feeder 2 is carried out by supplying water through a pipe branch with irrigation nozzles 7, the transport of the prepared slurry is carried out by means of a jet pump 8. For water supply of the pipe branch 7 and the jet pump 8, a water supply system is used.

The water supply system consists of a main valve 9, a control valve 10 and a pressure gauge 11 of the water supply system of the pipe branch 7, a control valve 12 and a pressure gauge 13 of the water supply system of the jet pump 8. Transportation of water and sludge is carried out through flexible pipes 14. The equipment is installed on support frames 15, 16. The source of water for the operation of laboratory equipment is the plumbing.

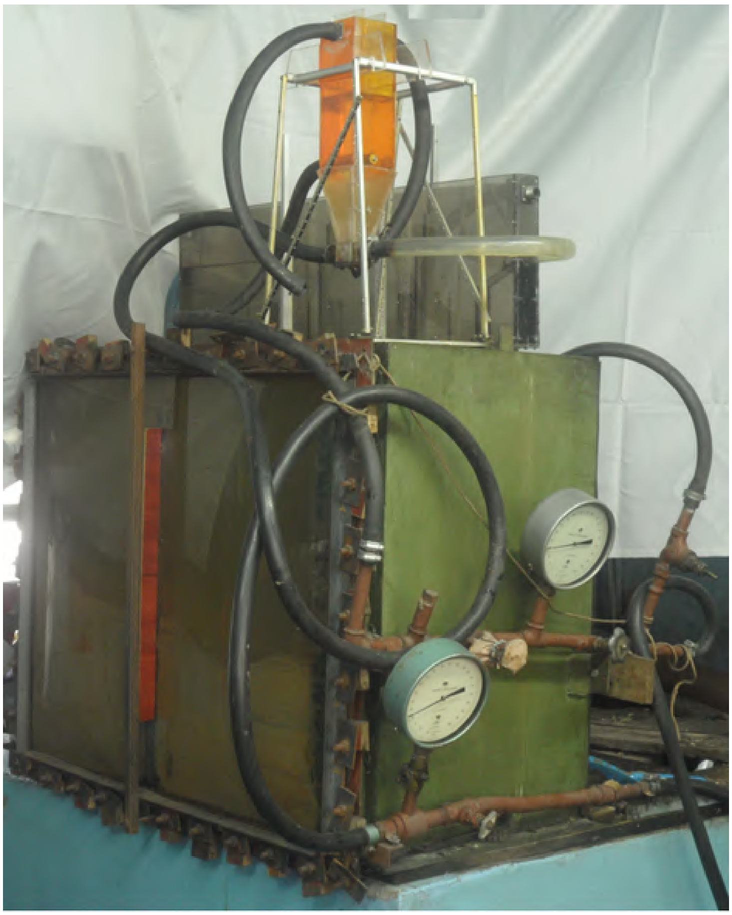
The following equipment was used to perform the necessary measurements:

1. Precision pressure gauge type MZM with a division value of 0.005 kgf/cm^2 (accuracy class 0.6).
2. Laboratory cylinder with a volume of 1 liter with a measurement accuracy of 2 ml.
3. Stopwatch "Agat" with a measurement accuracy of 0.5 s.
4. Scales VNC-2, a measurement accuracy of 2 g, TU 25-06-2068-82.
5. Scales RN-10C13M, a measurement accuracy of 5 g, GOST 7327-55.
6. Laboratory sieve SL-200 with cell of 0.1 mm, 0.2 mm, 0.315 mm, 0.4 mm, 0.5 mm, 0.63 mm, 1.25 mm, 2.5 mm.
7. Laboratory sieve shaker.
8. Drying cabinet.

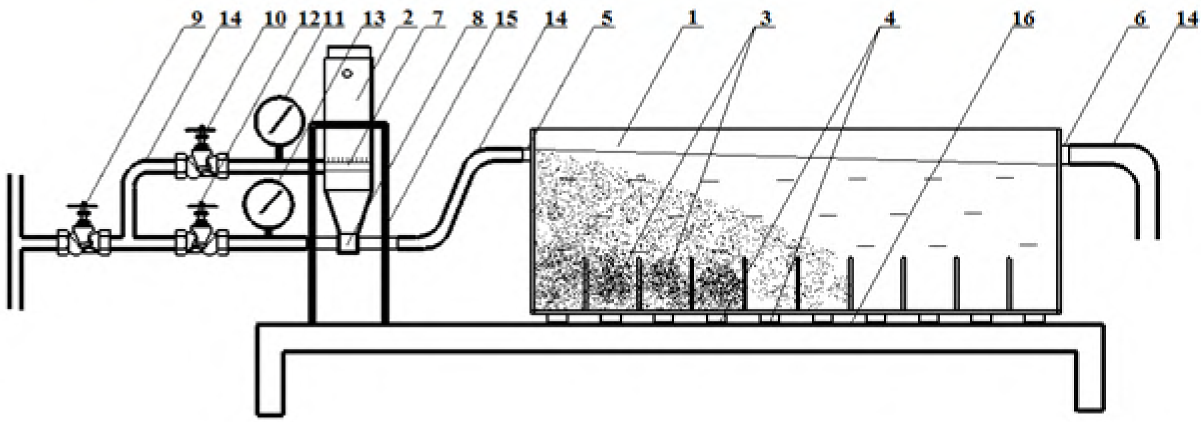
The complexity of modeling the process of gravitational processing of granular materials in a carrier horizontal flow lies in the need to take into account the horizontal and vertical movement of solid particles. At the same time, the following factors may have some influence on the solid particles motion process: co-flowing relative vertical and horizontal motion of solid particles; constraint of the solid particles movement; movement of solid particles relative to the carrier horizontal flow.

In order to take into account the above factors and quantify their influence on the process of granular materials gravitational processing, the obtained experimental data were processed. At the same time, the tasks of quantifying and assessing the need to take into account such factors were solved:

- movement of solid particles relative to the carrier horizontal flow;
- constraint of the solid particles movement;
- movement of solid particles in various parts of the gravity processing process in a horizontal flow.



(a)



(b)

Figure 3. Laboratory installation for the study of gravitational processing of granular materials based on HMC: (a) the general view of the installation; (b) a circuit scheme of the installation.

4. The movement of solid particles relative to the carrier flow

The study of the movement of solid particles from this size range was devoted to experimental studies carried out on a laboratory installation using a horizontal multi-section classifier HMC

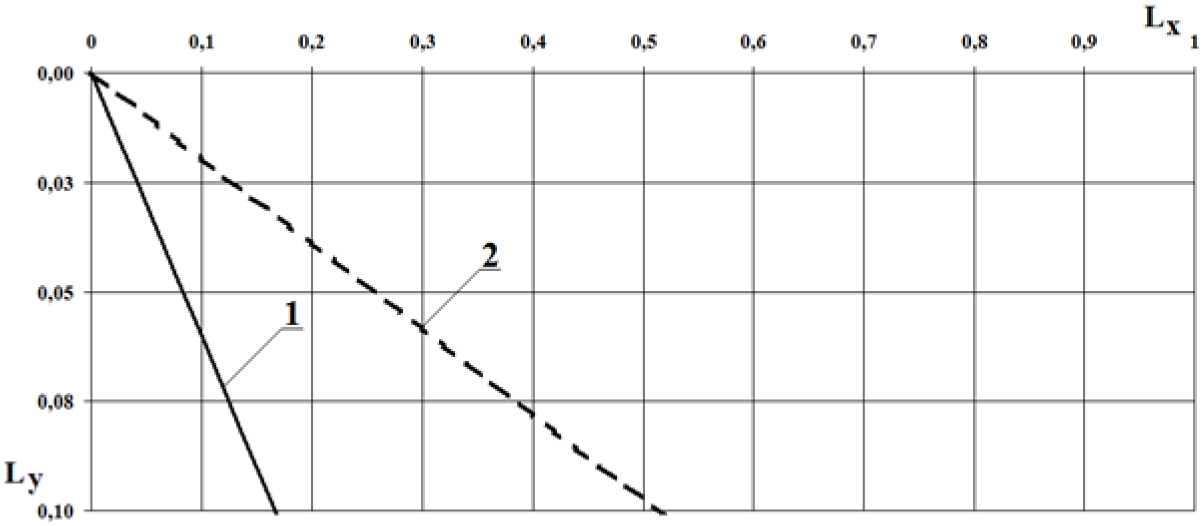


Figure 4. Theoretical trajectory of motion of rounded quartz particles: 1 – trajectory of movement of rounded quartz particles with size 0.2 mm; 2 – trajectory of movement of rounded quartz particles with size 0.1 mm

Table 1. Parameters of deposition of quartz particles with a particle size of < 0.2 mm, %

Slurry concentration, %	№ of the HMC compartment								$\sum$ №2-6
	2	3	4	5	6	7	8	9	91.2
3.0	37.4	18.4	14.9	12.1	8.4	4.7	2.7	1.4	94.1
6.0	44.1	18.6	14.1	10.5	6.8	3.5	1.6	0.8	92.0
10.0	40.1	18.8	14.2	11.1	7.7	4.3	2.5	1.2	93.4
13.0	42.3	18.6	14.0	11.0	7.6	3.6	2.0	1.0	89.7
19.0	36.0	18.0	14.6	12.2	9.0	5.6	3.2	1.5	91.2

(figure 3).

As a result of laboratory studies, the movement of rounded quartz particles in the size range < 1.8 mm and < 0.2 mm was studied. The calculation of the theoretical trajectory of particle motion was performed using the dependence (5) (figure 4).

The sedimentation process proceeded at an average horizontal flow velocity of 0.03 m/s. Processing of the experimental data showed that in the size range < 0.2 mm, more than 90% of solid particles sedimented in compartments No. 2-6, located in the theoretical area of sedimentation of rounded quartz particles with a size of 0.2 ... 0.1 mm (table 1, figure 5). Thus, the minimum value of the probability of sediment of a rounded quartz particles with a particle size of 0.2 ... 0.1 mm in the theoretical area of deposition is 90%. And when taking into account the presence of particles smaller than 0.1 mm in the used raw material, the theoretical area expands and the probability tends to 100%.

The purpose of laboratory studies was also to determine the effect of the concentration of solid particles in the feed on the deposition process. Processing of experimental data showed that the concentration of solids affects the constraint of particle movement, causing a decrease in the fall velocity (figure 6). In a detailed study of the mass characteristics of the material deposited in the area with a 90% probability of sediment of rounded quartz particles with a particles size of 0.1 ... 0.2 mm the average value of the mass difference in compartments No. 2-6 at a solid concentration in the slurry of 3% and 19% was 3%.

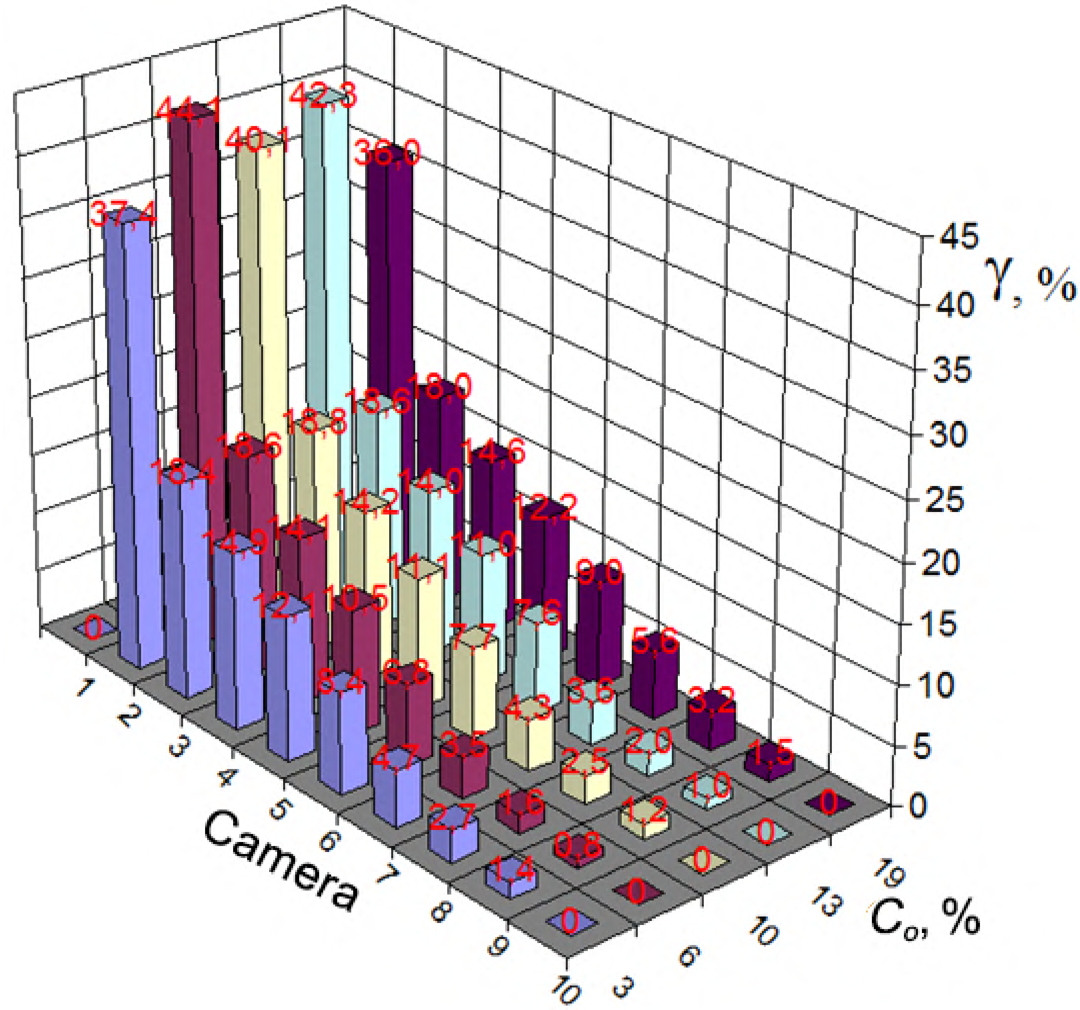


Figure 5. Sedimentation of rounded quartz particles with a particle size of < 0.2 mm when fed with a volumetric concentration (C_o, %).

Table 2. Average size of deposited quartz particles with a size of < 1.8 mm, %.

Slurry concentration, %	№ of the HMC compartment					
	1	2	3	4	5	6
3.0	0.41	0.337	0.285	0.24	0.202	0.174
6.0	0.404	0.341	0.278	0.229	0.192	0.165
10.0	0.398	0.347	0.276	0.227	0.19	0.165
13.0	0.403	0.36	0.283	0.231	0.194	0.164
19.0	0.391	0.361	0.28	0.232	0.197	0.168

An analysis of experimental data from laboratory studies of the movement of rounded quartz particles with a particle size of < 1.8 mm showed, that the influence of the solid concentration in the slurry within 0 ... 20% on the average size of the granular material deposited in the compartments does not go beyond 5%, and the average error is 1.6% (table 2, figure 7, 8).

This value indicates the fact of the insignificance of the influence of this factor on the process

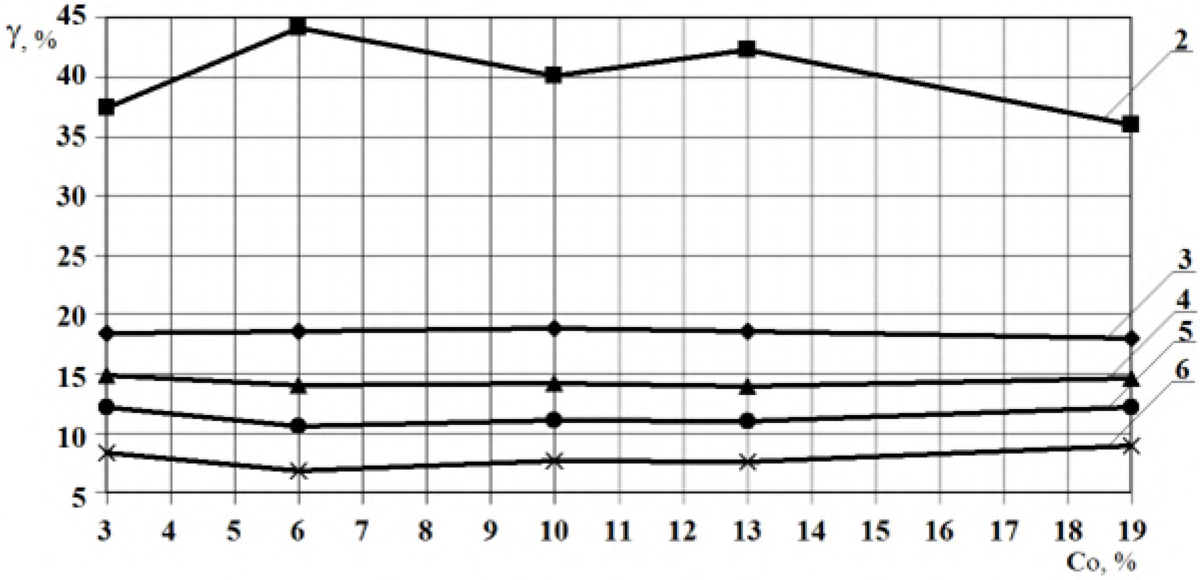


Figure 6. Influence of slurry concentration on the process of sedimentation of rounded quartz particles with a particle size of < 0.2 mm: 2, 3, 4, 5, 6 – compartments.

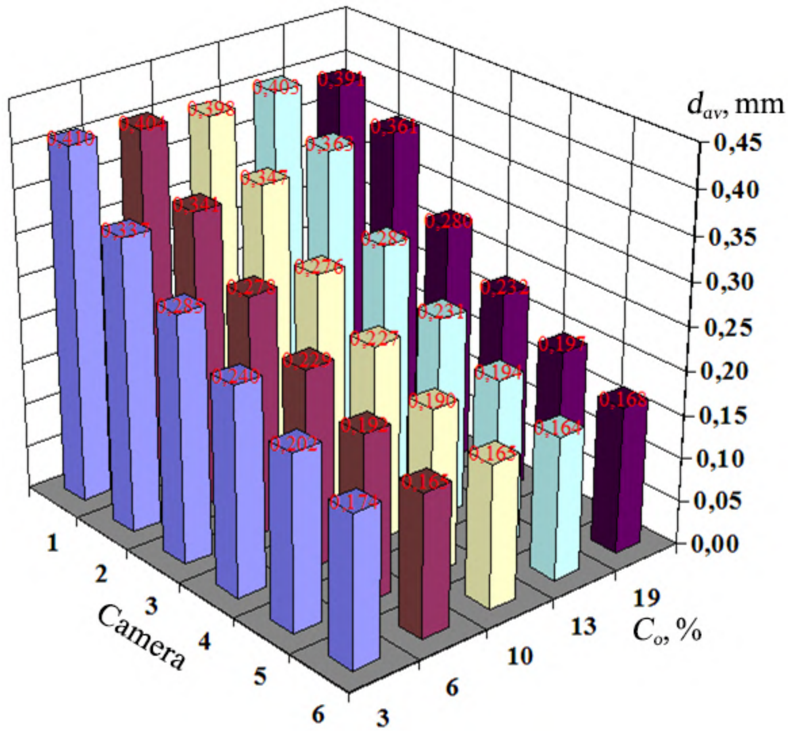


Figure 7. Sedimentation of rounded quartz particles with a particle size of < 1.8 mm when fed with a volumetric concentration (C_o, %).

of the solid particles sedimentation in the concentration range of 0...20%. Thus, the performed laboratory studies of the rounded quartz particles deposition process, under the influence of a horizontal carrier flow, confirm the relevance of the application of dependence (5) to calculate

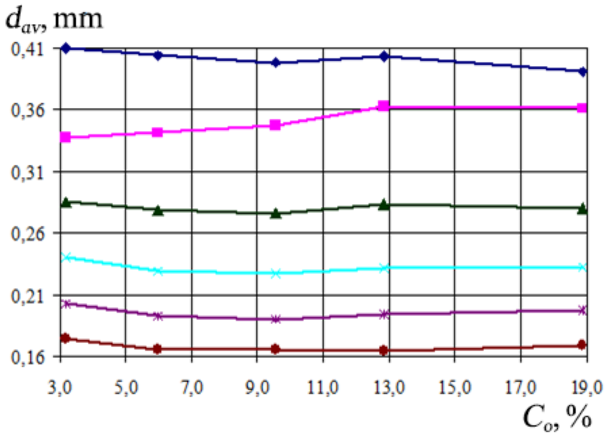


Figure 8. Influence of slurry concentration on the process of sedimentation of rounded quartz particles with a particle size of < 1.8 mm: 2, 3, 4, 5, 6 – compartments.

the parameters of the solid particles sedimantation with particle size < 1.8 mm and < 0.2 mm in the concentration range 0...20%.

5. Conclusions

The results of the theoretical studies of the interaction process between the flow part of a horizontal hydraulic classifier and the laminar slurry flow, which includes suspended solid particles, allow us to make the following conclusions:

1. The basis for the theoretical description of the gravitational sedimantation of solid particles during its passing and counter motion relative to the horizontal carrier flow was the Lagrange method.
2. At the velosity U_x of v_x the liquid movement, and the speed U_x^p of movement of the solid particle relative to the liquid, the absolute speed of the solid particle in passing motion with the carrier flow can be in the ranges: $1 - U_x^p < U_x$; $2 - U_x^p > U_x$; $3 - U_x^p = U_x, v_x = 0$.
3. An initial theoretical dependence was obtained to determine the path traveled by a solid particle under the conditions of gravitational sedimantation under the action of a horizontal carrier flow, which takes into account possible scenarios for the relative motion of a solid particle and liquid.

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References

[1] Babets Y K, Adamchuk A A, Shustov O O, Anisimov O O and Dmytruk O O 2020 *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu* (6) 5–14 ISSN 20712227 URL https://doi.org/10.33271/nvngu/2020-6/005
[2] Sobko B, Lozhnikov O and Drebenshtedt C 2020 *E3S Web of Conferences* **168** 00037 ISSN 2267-1242 URL https://doi.org/10.1051/e3sconf/202016800037
[3] Khomenko O, Rudakov D and Kononenko M 2011 Automation of drill and blast design *Technical and Geoinformational Systems in Mining* (CRC Press) pp 271–275 URL https://doi.org/10.1201/b11586-45

[4] Shcherbakov P, Tymchenko S, Bitimbayev M, Sarybayev N and Moldabayev S 2021 *Mining of Mineral Deposits* **15**(2) 25–34 ISSN 24153435 URL https://doi.org/10.33271/mining15.02.025
[5] Lazar M, Apostu I M, Faur F and Rotunjanu I 2021 *Mining of Mineral Deposits* **15**(2) 124–133 ISSN 24153435 URL https://doi.org/10.33271/mining15.02.124
[6] Bondarenko A and Naumenko R 2019 *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu* (4) ISSN 20712227 URL https://doi.org/10.29202/nvngu/2019-4/14
[7] Bondarenko A, Maliarenko P O, Zapara Y and Bliskun S 2020 *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu* (5) 26–32 ISSN 20712227 URL https://doi.org/10.33271/nvngu/2020-5/026
[8] Cherniaiev O, Pavlychenko A, Romanenko O and Vovk Y 2021 *Mining of Mineral Deposits* **15**(4) 99–107 ISSN 24153435 URL https://doi.org/10.33271/mining15.04.099

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Application of mining technology by the combination of ANSH equipment to longwall in Seam 6 of Mao Khe coal mine, Viet Nam

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Abstract. Currently, in the Quang Ninh coalfield, exploiting the seams with medium thickness and dip angle of over 50 degrees is often difficult, so labor productivity and safety are low. It is necessary to research and apply advanced mining technology to medium thickness seams with dip angle of over 50 degrees in order to improve efficiency and safety. Studying the actual production in the Mao Khe coal mine shows that the mining technology for the condition of the seam with medium thickness, and dip angle over 50 degrees is mainly mining technology by drilling and blasting. This technology has the disadvantage of low labor productivity and unsafety. In this paper, the authors have researched and proposed mining technology by the combination of ANSH equipment to exploit the longwall in Seam 6 of Mao Khe coal mine. This is a fully mechanized mining technology, coal cutting by plow, combined with shield. Analysis of economic and technical indicators shows that this technology has been more effective and productive than the mining technology currently applied in other coal mines. This application will benefit not only Mao Khe coal mine, but also to other coal mines of Quang Ninh coalfield with similar coal seam conditions.

1. Introduction

Fully mechanized mining technology is a type of technology that uses shearer or plow with mechanized shield to extract coal seams [1–3]. This technology has been used in many countries, especially in China and European countries [4], where mechanized mining techniques applied to coal seams are also relatively effective.

In recent years, mechanized mining technology that uses shearer has been applied to a number of underground mines in the Quang Ninh coalfield, Vietnam and it has achieved certain initial effects [5–9]. However, the fully mechanized mining technology that uses a plow is still a new technology and has not been adequately researched and invested in underground mines in the Quang Ninh coalfield. This is a mechanized mining technology that is applied to the seams with medium thickness and dip angle of over 50 degrees.

Currently, in Quang Ninh coalfield, there are many underground mines managed by Vietnam national Coal - Mineral industries Corporation. In which, the reserves of coal seams of medium thickness and dip angle of over 50 degrees account for a relatively large proportion [10]. The condition of these seams belongs to most coal mines such as: Mao Khe, Nam Mau, Vang Danh, Uong Bi, Ha Lam, Nui Beo, Hon Gai, Duong Huy, Thong Nhat, Ha Long, Quang Hanh, Mong Duong and Khe Cham. Due to the geological conditions of the seams at different coal mines, the Vietnam national Coal - Mineral industries Corporation has also selected and applied many different types of mining technologies and methods, but it has not yet brought about the expected efficiency [11]. Mining technology by drilling and blasting is the main technology that has been applied to coal seams of medium thickness, dip angle of over 50 degrees, this is a manual mining technology. The disadvantages of this technology are low safety, interruption in the technological chain, releasing harmful gases, and low productivity.

To eliminate the disadvantages of the drilling and blasting mining method, along with the determination to modernize technology in underground mining. For many years, the Vietnam national Coal - Mineral industries Corporation has coordinated and directed coal mines in Quang Ninh coalfield to actively research and select suitable and effective mining technologies for coal seams of medium thickness, dip angle of over 50 degrees. From the above practical issues, the article has researched and proposed a mining technology by the combination of ANSH equipment for longwall in Seam 6 of Mao Khe coal mine. Mining technology using a combination of ANSH equipment has been applied in some Eastern European countries and has brought good results when exploiting coal seams of medium thickness, dip angle of over 50 degrees. This is a fully mechanized mining technology, coal cutting by plow, combined with shield and it is applied to the seams of medium thickness, dip angle of over of 50 degrees. On the basis of the research results of the article, Mao Khe coal mine can apply and deploy these proposal designs in actual production to improve working efficiency in the longwall face, thereby increasing mining efficiency and productivity.

2. Geological features of the longwall in Seam 6 of Mao Khe coal mine

The thickness of the seam varies from 0.8 to 3.75 m, with an average of 1.82 m, belonging to the medium thickness and very unstable type. The dip angle of the seam varies from 57° to 70°, with an average of 61°.

Roof: located directly on the seam, there is a claystone layer interspersed with coal- clay and thin layers of coal forming a layer with a thickness of $0.2 \dots 2.2$ m, which is easy to collapse and separate during mining, followed by layered siltstone with a total thickness of $8 \dots 25$ m of medium stable hard rock. Many interstitial places in the siltstone are thin layers of sandstone. Next, the siltstone is a thick and stable layer of sandstone.

Floor: located directly below the seam, it is a soft rock layer consisting of: claystone interlaced with coal-clay lenses with a total thickness of $0.21 \dots 1.8$ m. The weak rock layer is followed by a thin to medium layered siltstone layer with a total thickness of $14 \dots 20$ m. The distribution under the siltstone is a layer of fine to medium grained sandstone with a total thickness of $5 \dots 30$ m. Rocks are sustainable.

Table 1. Some average physical and mechanical parameters of the roof and floor [12].

Rock unit	σ_n (Mpa)	σ_k (Mpa)	γ (T/m^3)	φ (degree)	C (Mpa)
sandstone	94.2	10.1	2.64	33	12.1
siltstone	45.8	5.8	2.6	32	10
claystone	17.1	2.9	2.57	24	8.9

3. Mining technology by the combination of ANSH equipment

3.1. Mechanized equipment in the longwall

3.1.1. Combination of equipment type ANSH Currently, in Eastern European countries, two types of mechanized mining equipment combinations have been manufactured and applied for coal seams with medium thickness, dip angle of over 50 degrees. Combinations include: 1ASHMG, 1ANSH and 2ANSH. The basic technical characteristics of the above equipment combinations are shown in table 2.

Table 2. Technical characteristics of ANSH mining equipment combinations [13].

No	Parameters	Unit	1ASHMG	1ANSH	2ANSH
1	Applicable seam thickness	m	1.2 ... 2.2	0.7 ... 1.3	1.1 ... 2.2
2	Applicable seam dip angle	degree	50 ... 80	35 ... 90	35 ... 90
3	Load capacity of shield for 1 m^2, (not less than)	kN/m^2	200	170	240
4	Load capacity of the shield (not less than)	kN	500	800	800
5	The displacement of the shield (not more than)	m	0.63	0.63	0.63
6	Step of installing a shield (not more than)	m	1.0	1.0	1.0
7	Height of the shield (min-max)	mm	1000 ... 2200	670 ... 1300	980 ... 2200
8	Width of the shield	mm	960	960	960
9	The length of the complex	m	45	60	60

Based on the geological conditions of the mine, on the basis of the technical characteristics of the mining equipment combinations, select the 2ANSH combination or the type with equivalent technical characteristics for the application of coal seam mining of medium thickness, dip angle of over 50 degrees at Mao Khe coal mine. Through analysis and field survey, it is shown that this equipment combination is suitable for the conditions of the longwall in Seam 6 of Mao Khe coal mine.

3.1.2. Shield The shield used in this equipment complex is the 2ANSH shield combination (figure 1) and the technical characteristics are shown in table 2.

3.1.3. Coal cutting To extract coal in the longwall in Seam 6, the Mao Khe coal mine has chosen the plow 1ASHM (figure 2) with specifications shown in table 3.

Table 3. Technical characteristics of coal plow 1ASHM.

No	Parameters	Unit	Value
1	Plow productivity	T/minute	2.5
2	Plow speed	m/s	1.6
3	Engine power	kW	140
4	Plow width	mm	760
5	Plow length	m	6

Figure 1. 2ANSH shield complex [14].

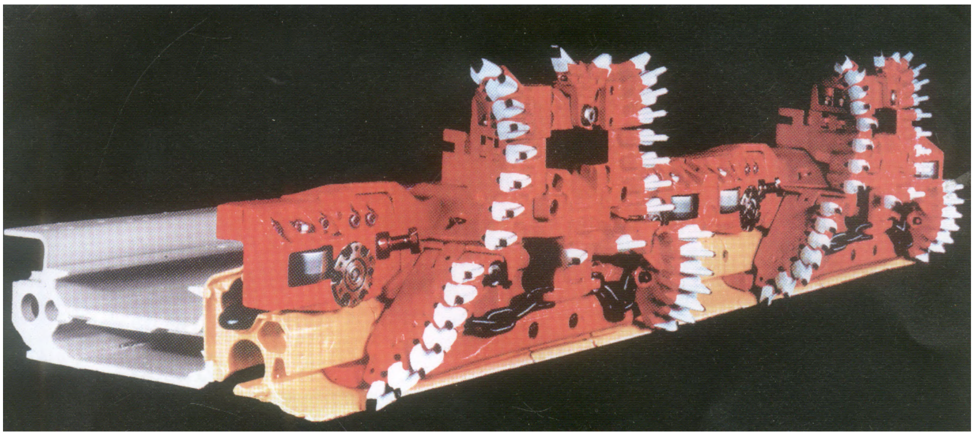

Figure 2. Coal plow 1ASHM [14].

3.1.4. Emulsion pumping station To provide emulsion for equipment in the longwall, Mao Khe coal mine has selected pump code CND-200/32, its basic technical characteristics are shown in table 4.

Table 4. Characteristics of CND-200/32 pumping station.

No	Parameters	Unit	Value
1	Rated pressure	Mpa	32
2	Engine power	kW	2x 55
3	Volume of solution tank	liter	1600
4	Pump size (length x width x height)	mm	2700 x1200 x 1000
5	Solution tank size (length x width x height)	mm	3200 x 1200 x 1100
6	Pump weight	kg	2000
7	Solution tank weight	kg	1600

3.2. Technological process of mining in the longwall face

The process of this mining technology is carried out in 3 stages as follows:

3.2.1. Stage 1: exploiting to install the shields Exploiting to create space to install the shields is done by manual drilling and blasting method, supporting the longwall face by wood. When cutting and supporting in the strike direction of 4 web cuts, install the first shield, then exploit in the strike direction of one web cut to continue installing the next shield. The work of cutting and installation of shields is carried out sequentially until the number of installed shields is completed in the longwall. During the process of cutting and installing the shield, the distance from the longwall face to the shield position must not exceed 3 meters. Next, install the plow system, pumping station, communication signal equipment, automatic control device and other auxiliary equipment.

3.2.2. Stage 2: exploiting the longwall using a combination of shield Coal cutting in the longwall follows in dip direction of the seam, the cutting of coal in the longwall face by the plow system. The plow moves along the longwall face and cuts coal from the floor to the roof of the longwall. After cutting the entire length of the longwall face, the plow is returned to its original position before moving the shield.

3.2.3. Stage 3: dismantling the shield complex, moving to the next mining lift When the longwall is exploited to about 8 to 12 meters from the transport level, proceed to create a space for the longwall face to dismantle the shield system. The work of dismantling the shield is carried out in turn from the ventilation brake incline to the transport brake incline. The recovery shields are transported to the ventilation level to be installed in service of mining for the new lift.

The diagram of mining technology by the 2ANSH shield system is shown in figure 3 and the process of coal cutting in the longwall face using a plow is shown in figure 4.

3.3. Support plan for the longwall face in Seam 6 of Mao Khe coal mine

3.3.1. Arrangement of shield (figure 5) Based on the mine pressure of the longwall face, the load capacity of the shield (the load capacity of the rig for 1 m^2 is greater than 240 kN/m^2 and the load capacity of the shield is not less than 800 kN). At the same time, based on the experience of exploiting the longwall using a combination of shield equipment from a number of Eastern European countries and Ukraine, the design of the support plan for the longwall face is as follows:

- The length of the longwall (a lift): 60 m.
- Distance between shields in the complex: 1.0 m.
- Number of shields in the complex: 60 shields.

3.3.2. Moving the shield in the longwall Moving process of the hydraulic shield is as follows: Two adjacent auxiliary shields on each vertical segment are depressurized by hydraulic control series. Auxiliary shields are pushed toward the face by stretching of the hydraulic jacks. Then, the main shield groups are depressurized by hydraulic control panels and the main shields are pulled toward the face by the shrink of the hydraulic jacks. Main and auxiliary shields are set in a straight line by hydraulic jacks. The process of moving the shield is shown in figure 6.

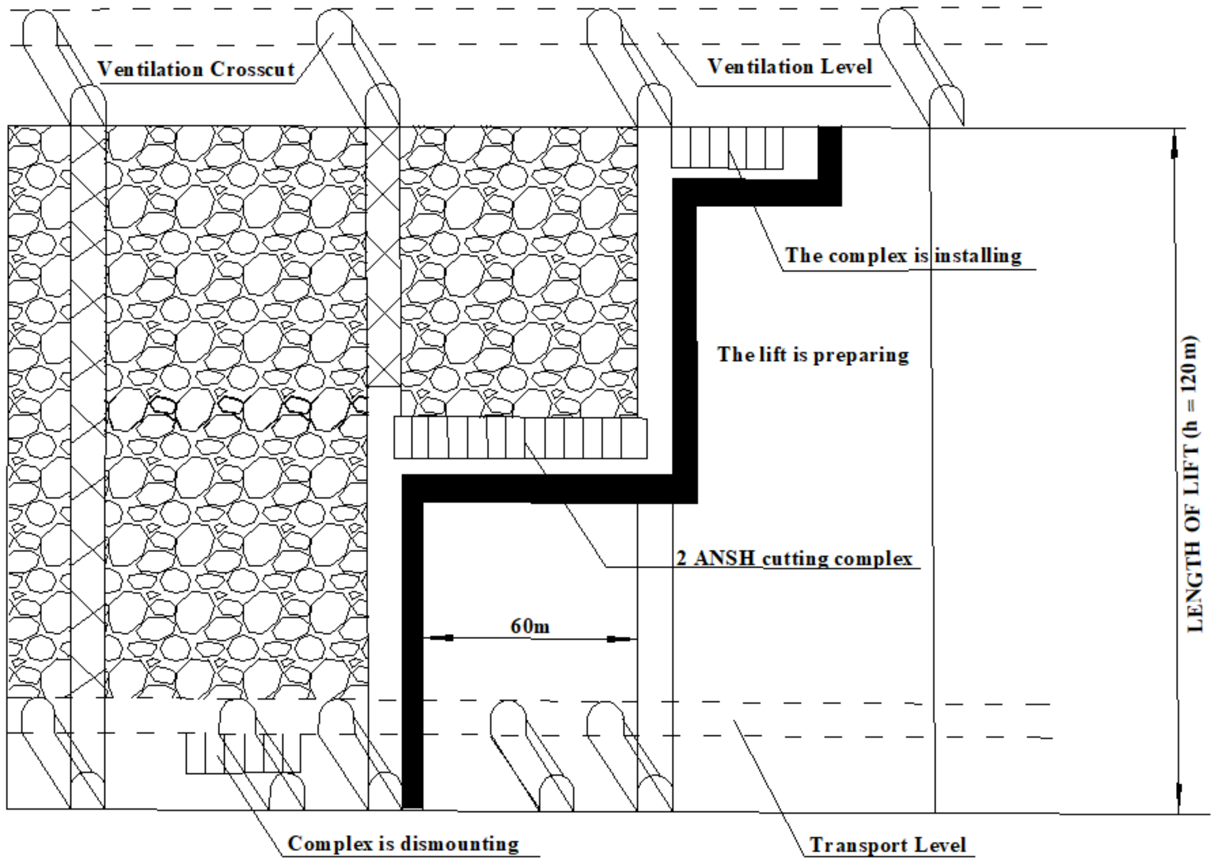

Figure 3. Diagram of mining technology applying 2ANSH combination [15].

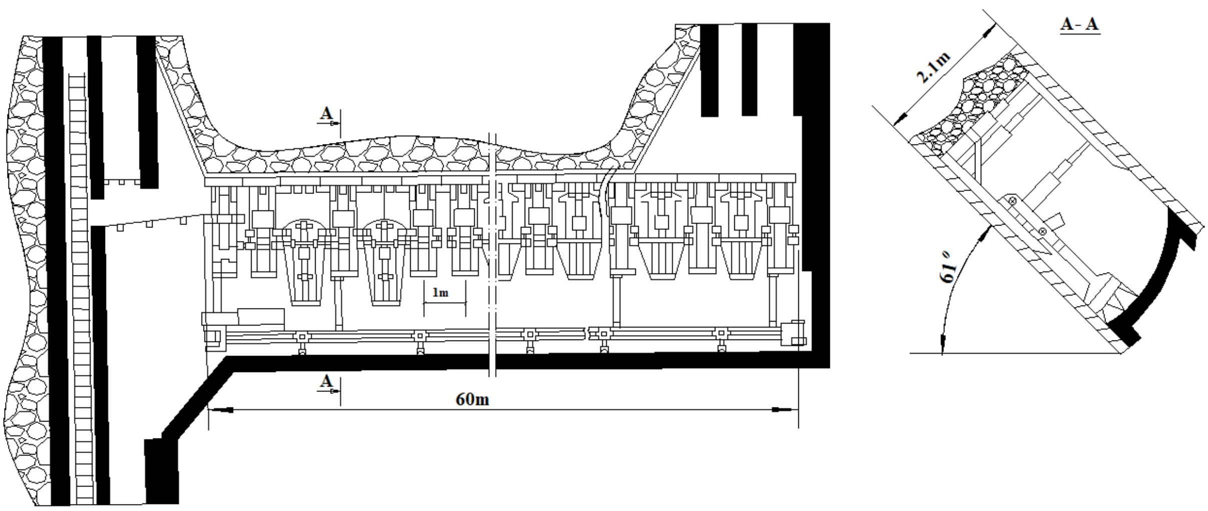

Figure 4. Process of coal cutting in the longwall face using a plow [15].

3.4. Operation scheme and human resource arrangement for the longwall in Seam 6 of Mao Khe coal mine

The production tasks in the longwall in Seam 6 are organized and performed in cycles. A cycle of eight web cuts is completed within three shifts, equivalent to the face moving progress of

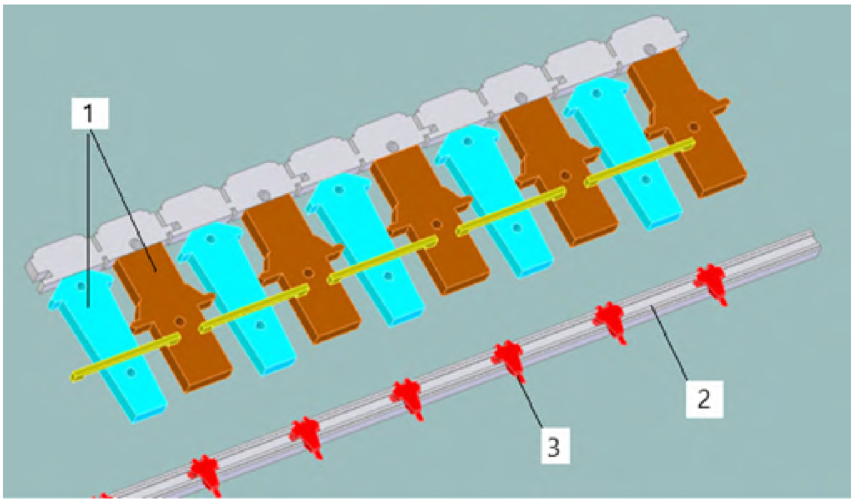

Figure 5. Arrangement of shield in the longwall [16]: 1 – shields; 2 – frame of scraper conveyors; 3 – coal plow.

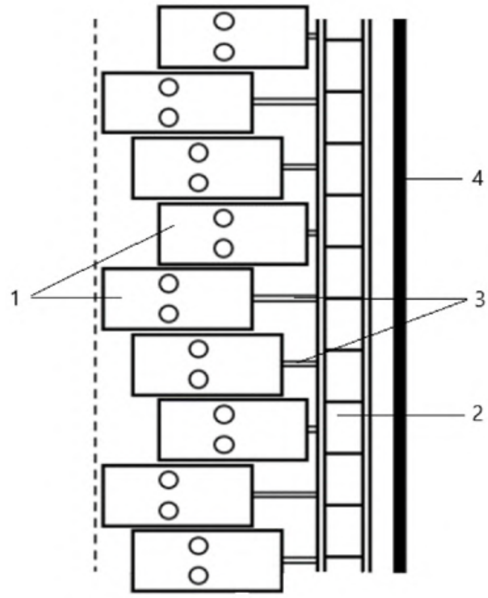

Figure 6. The process of moving the shield in the longwall: 1 – shields; 2 – scraper conveyors; 3 – hydraulic jacks; 4 – longwall face.

four meters per day (figure 7). A web cut includes the following stages: cutting face and shield shifting with an advance rate of 0.63 m, strengthen the longwall and preparing for a new web cut. The inspection and maintenance of equipment complex are carried out at the end of shift III, including maintenance, repair, and replacement of spare parts if necessary for the plow, roof supports, conveyors, electrical equipment and emulsifier pump systems, dust filter system, power supply system, water supply system, methane warning system, and pressure test of roof supports. The number of workers in the longwall face is arranged depending on the specific work of each shift. According to calculations, the required number of workers is 48 people, in which, each shift is arranged for 16 people (figure 8).

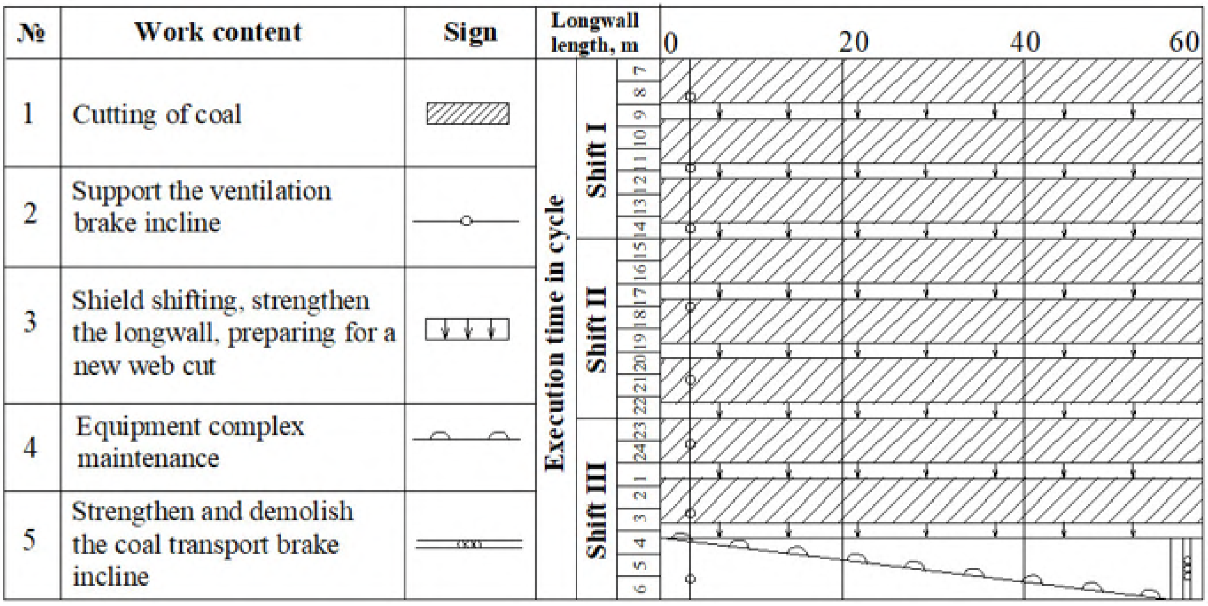

Figure 7. The operation scheme in the longwall in Seam 6 of Mao Khe coal mine.

№	Work content	Worker arragement				Execution time in cycle
		Shift I	Shift II	Shift III	Total	Shift I, Shift II, Shift III
1	Cutting of coal and shifting shield	2	2	2	6	
2	Strengthen the longwall and coal transport brake incline	2	2	2	6	
3	Support the ventilation brake incline	4	4	4	12	
4	Transfer materials	2	2	2	6	
5	Equipment complex maintenance	-	-	(8)	(8)	
6	Strengthen and demolish the coal transport brake incline	-	-	(8)	(8)	
7	Electromechanical manager	1	1	1	3	
8	Conveyor operation in transport drift	2	2	2	6	
9	Operation of emulsion pumping station	1	1	1	3	
10	Operation of winch	1	1	1	3	
11	General production manager	1	1	1	3	
	Total	**16**	**16**	**16**	**48**	

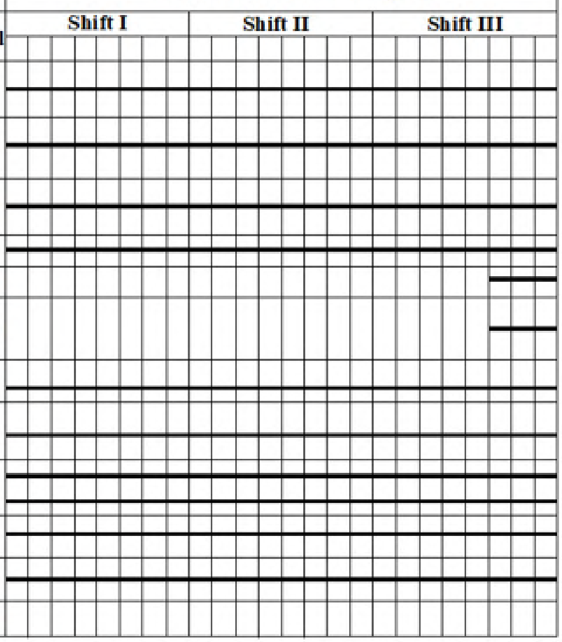

Figure 8. Chart of human resource arrangement in the longwall in Seam 6 of Mao Khe coal mine.

3.5. Economic and technical indices

After researching and application of mining technology by the combination of ANSH equipment to longwall in Seam 6 of Mao Khe coal mine, which is exploited by fully mechanized technology, with the above equipment combination, the calculated main economic-technical indices are shown in table 5.

Table 5. Economic and technical indices of the longwall face in Seam 6 of Mao Khe coal mine.

No	Indices	Unit	Amount
1	Average thickness of seam	m	2.1
2	Average dip angle of the seam	Degree	61
3	Volumetric weight of coal	T/m^3	1.61
4	The length of the longwall (a lift)	m	60
5	The length in dip direction (a lift)	m	120
6	The height of coal cutting (longwall)	m	2.1
7	The length in strike direction	m	540
8	Face advance in one web cut	m	0.63
9	Face advance in a day and night	m	4.0
10	The type of shield used in the longwall (shield complex)		2ANSH
11	Coal output of a day and night	ton	777
12	Cycle completion coefficient	-	0.8
13	Face advance in a month	m	104
14	Capacity of longwall face	ton	207.790
15	Number of workers in a day	worker	48
16	Direct labor productivity	T/labor	16.1
17	Consumption of wood for 1000 tons of coal	m^3	28.7
18	Consumption of roadway preparation for 1000 tons of coal	m	6.5
19	Consumption of emulsifying oil for 1000 tons of coal	kg	13.7
20	Consumption of clean water for 1000 tons of coal	m^3	13.1
21	Consumption of cutting teeth for 1000 tons of coal	unit	3.0
22	Consumption of compressed air for 1000 tons of coal	m^3	433
23	Coal loss	%	28.9

4. Conclusions

(i) According to the general assessment of geological and technical conditions, reserves in Quang Ninh coalfield are about 3 billion tons, of which coal reserves of steep seams account for more than 30%. At the Mao Khe coal mine, the steep seams account for about 47.5%, of which the thick seams are 51% and the remaining 49% are the medium thick ones. Therefore, it is very necessary to research and select mining technology to ensure the economic and technical requirements to exploit the seams of medium thickness and dip angle of over 50 degrees at Mao Khe coal mine.

(ii) In the condition that the coal seam has an average thickness of 1.8 to 2.5 m, the dip angle of the seam is from 45° to 90°, some countries such as Ukraine have applied the mining technology diagram in the slope direction, mining technology uses a combination of mechanization with a plow, and support for longwall face by the shield. In fact, the advantage of this mining technology is to reduce the unsafety risks from the collapse of roof during the exploitation of thin to medium-thick seams, dip angle of over 45°. This complex has a small cutting step and the movement of the combination is due to the self-sliding mechanism on the slope due to the impact of the collapsed rock mass above the shield and the self-weight of the equipment combinations. Based on the geological conditions of the mine and the technical characteristics of the mining equipment combinations, this study proposed and selected a combination of 2ANSH equipment or a type with equivalent technical characteristics to exploit coal seam of medium thickness, dip angle of over 45° at

Mao Khe coal mine.

(iii) The application of mining technology using a combination of 2ANSH equipment to the condition of the longwall in Seam 6 of Mao Khe coal mine, according to calculations, it has met the requirements of economic and technical indices when mining. Labor productivity 16 tons/worker-shift, low coal loss, high safety level (table 5).

Acknowledgments
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References

[1] Vu D T and Tran V T 2005 *Underground coal mining technology* (Ha Noi: Transportation publisher)
[2] Ning Y, Shi Y and Qi Q 2006 *Strata control and technology optimization for fully mechanized coalface using top-coal caving* (Xuzhou: China University of Mining and Technology Press)
[3] Syd S P, Guo W and Chen J 2010 *Longwall mining* (Beijing: Beijing science press)
[4] Syd S P 2013 *Coal mine ground control* (Xuzhou: China University of Mining and Technology Press) ISBN 978-7-5646-1880-3
[5] Vu T T 2022 *Mining of Mineral Deposits* **16** 127–134 ISSN 2415-3435, 2415-3443 URL `http://mining.in.ua/2022vol16_1_16.html`
[6] 2021 Mining passport for fully mechanized longwall in Seam 11 and Seam 7 Tech. rep. Ha Lam Coal Company – Department of mining technology Quang Ninh
[7] 2022 Mining passport for fully mechanized longwall in Seam 11 Tech. rep. Nui Beo Coal Company – Department of mining technology Quang Ninh
[8] 2022 Mining passport for fully mechanized longwall in Seam 11 Tech. rep. Duong Huy Coal Company – Department of mining technology Quang Ninh
[9] 2022 Mining passport for fully mechanized longwall in Seam L7 Tech. rep. Mong Duong Coal Company – Department of mining technology Quang Ninh
[10] Dao H Q 2016 *Journal of Mining Industry* **4** 9–15
[11] 2019 Report of applying mining technology to the condition of thick coal seams, steep angles in Quang Ninh coalfield Tech. rep. Institute of Mining Science and Technology Ha Noi
[12] 2021 Report on assessment of geological conditions at Mao Khe coal mine for deep mining Tech. rep. Mao Khe Coal Company – Department of Geodesy and Mine Geology Quang Ninh
[13] Vu D N 2007 *Research and improve mining technology of steep, medium-thick seams in Mao Khe area* Master's thesis Hanoi University of Mining and Geology Hanoi, Vietnam
[14] 2009 Assessing the effectiveness and proposing the development direction to apply mechanization technology of thin slope seams with 2ANSH shield at underground mines in Quang Ninh coalfield Tech. rep. Institute of Mining Science and Technology Ha Noi
[15] Tran V T, Vu T T, Nguyen N B and Le D V 2008 Applied research of mining technology by plough-scraper to the conditions of Ha coal seam of Mongduong mine form −100 to −160 levels *In proceedings of International conference on advances in mining and tunneling* (Ha Noi City: Publishing house for science and technology) pp 84–89
[16] Dao T C, Do M P, Dang V C and Nguyen Q T 2017 *Journal of Vietnam Science and Technology* **22** 60–64

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Prospects for the use of a vibratory jaw crusher with an inclined crushing chamber for processing of brittle materials

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Prospects for the use of a vibratory jaw crusher with an inclined crushing chamber for processing of brittle materials

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Abstract. Obtaining a powder product from brittle materials is associated with significant difficulties: an insufficient number of production capacities as well as with their low efficiency. This indicates relevance and need for research aimed at creating new designs and technological schemes. Glass containers were selected for research from among all types of glass waste. Presented are a structural diagram and description of a horizontal pendulum impact tester, on which studies were carried out on destruction of a bottle by impact load. The impact tester gives an opportunity to determine impact energy, impact speed, acceleration, movement of the impactor. An analysis of the above figures shows that one blow is enough to destroy a bottle. Rational mode is when impact load is distributed along the length of the bottle. This mode can be implemented in a vibratory jaw crusher with an inclined crushing chamber, which includes the following main elements: a passive jaw located on shock absorbers, an active jaw pivotally mounted in the body and connected to it by means of elastic links, a two-shaft inertial vibration exciter. The presented granulometric characteristic of the crushed bottle shows a high efficiency of using a vibratory jaw crusher. The yield of the product sized less than 5.5 mm was 95%, and that sized less than 100 microns - 16%. The crusher has enough parameters to adjust particle size distribution over a wide range.

1. Introduction

In nature, there are a number of materials (quartzite, basalt, marble, etc.) with high compressive strength and low resistance to impact loads. At the same time, a significant percentage of the equipment used for their disintegration consist of jaw and cone crushers, in which the destruction of the material is carried out by compression [1]. In high-tonnage production, these metal-intensive overall machines currently have no adequate replacement. In the technological schemes for obtaining fine-grained and powder materials with a productivity of 1…10 t/h and a size of the raw material corresponding to average crushing, there is a need to improve existing grinding methods [2] and develop new grinders that combine crushing and grinding operations in one design.

Ideally brittle materials, along with diamond and quartz, include glass, which can serve as a standard in determining the efficiency of using crushing and grinding equipment. At the same time, interest in obtaining glass powder is currently growing in the world. This problem is relevant, because it is associated with a wide range of properties that make simple and special purpose glass powders a versatile material [3–5]. Depending on their composition, powders can meet a variety of requirements and can be used in the sphere of electrical insulation, sealing or bonding of various materials, for 3D printing of complex glass bodies, as additives in polymers, concrete, etc. [6–8]. Powder production is a complex and energy-intensive process [9], which includes all stages of glass production. The raw materials for glass production are low-iron quartz sands, soda ash, limestone, dolomite, etc., which require preliminary enrichment, washing, drying, and grinding. The resulting glass mass is again subjected to crushing, grinding, separation, which creates a high cost of production.

At the same time, hundreds of thousands of tons of glass waste are generated annually, but only a small part of them goes into secondary resources [10]. It is known that one ton of cullet saves 1.5 tons of mineral glass raw materials, incl. 100-130 kg of soda ash, 40-50 kg of sodium sulfate and 300-350 kg of quartz sand. Recycling glass allows to save huge areas of land that otherwise should turn into environmentally hazardous landfills [11]. This testifies to the relevance and necessity of carrying out analytical, experimental, design developments aimed at increasing efficiency of obtaining fine-grained and powder materials directly of glass wastes.

Study purpose is to evaluate the effectiveness of using vibratory jaw crushers for processing brittle materials to obtain a fine-grained and powder commercial product.

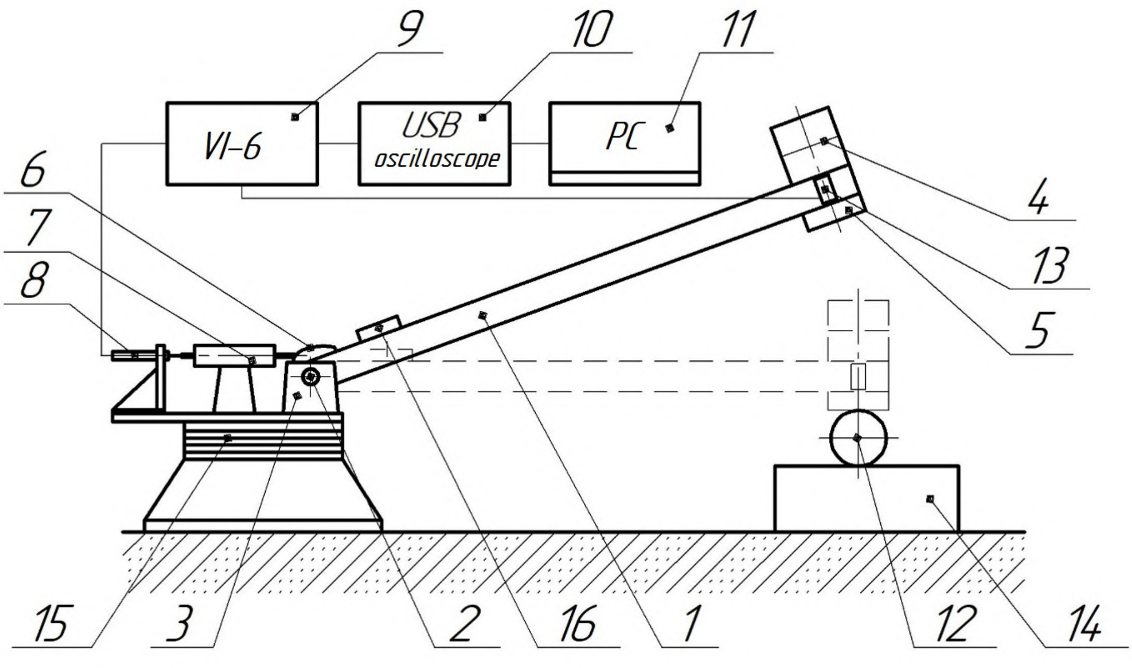
2. Results

A distinctive feature of glass is its high compressive strength and low impact resistance [12, 13], therefore, glass is destroyed by mechanical action without noticeable plastic deformation, which predetermines the development of crushers with the impact principle of loading the material.

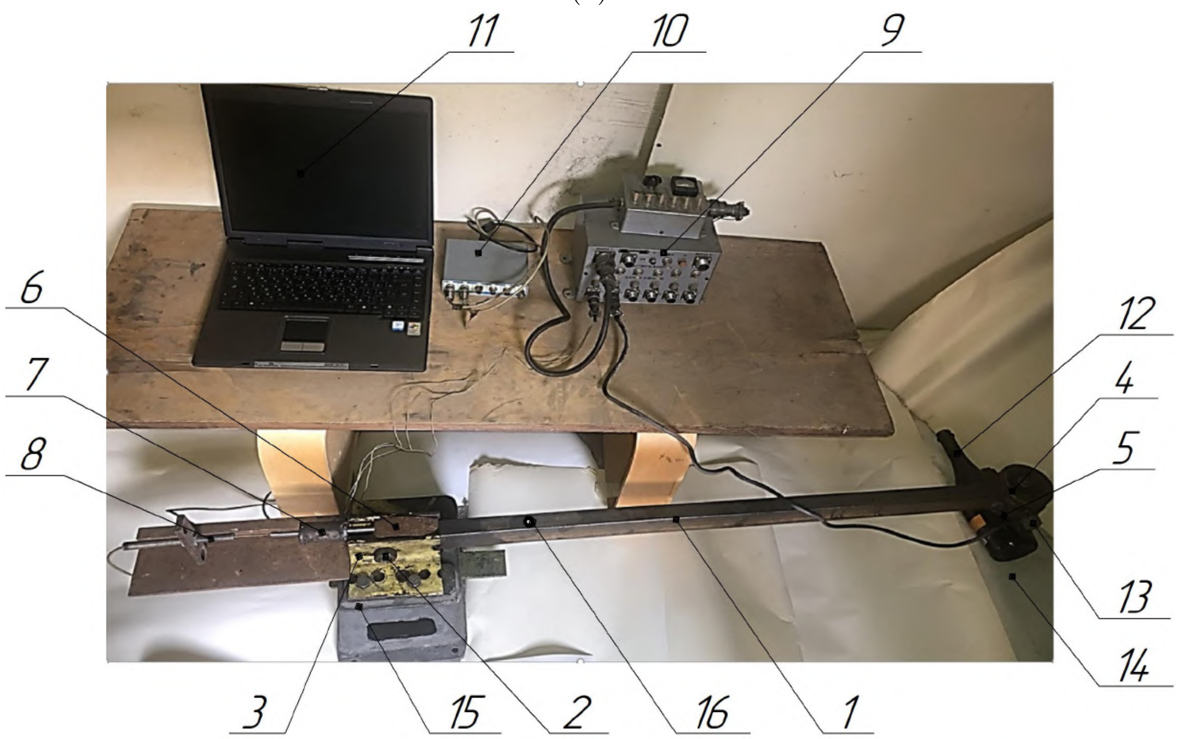
From among all types of glass waste, glass containers were selected for the research; they have a fairly well-developed collection scheme at collection points [14]. It was also taken into account that the volumetric shape leads to a sharp change in filling of the crushing chamber with material during the process of loading.

Interaction of bottles with the impactor was studied on the developed laboratory installation for destruction of rocks, which is a horizontal pendulum impact tester; its structural diagram is shown in figure 1.

The laboratory installation includes a pendulum (1) with its suspension axis (2) fixed in the bearing units of the housing (3). At the free end of the pendulum there is an impact assembly, consisting of a replaceable load (4) and an impactor (5). The centers of mass of the load and the impactor are located on a common vertical axis at a distance of 1 m from the axis of the pendulum suspension. Fastening of the impactor allows you to set various profiles of the working surface that interacts with glass. The lifting (dropping) height of the impactor is determined by a measuring system containing a curvilinear bar (6) rigidly connected to the pendulum suspension axis and a following mechanism (7). The mechanism is presented in the form of a cylinder with a piston and a clamping spring inside. The rod fixed on the piston has one end in contact with the curvilinear bar, and the other end is connected to the displacement sensor (8). The system works as follows. When the pendulum is raised, the curvilinear bar rotates along with the suspension axis, and so it moves the following mechanism rod according to the given dependence. Accordingly, the displacement sensor rod also moves; the signal from this sensor passes through the VI 6-6tn (9) vibration measuring equipment, the USB oscilloscope (10) and it registers the height of the load drop on the laptop screen (11). This system also allows you to track the nature of interaction of the impactor with the material under study (12). For the same purpose, an acceleration sensor (13) is fixed on the impact assembly; it records changes in acceleration in the vertical plane. At the initial moment of testing, the working surface of the impactor is installed on the surface of the sample located on a massive base (14). Next, the pendulum suspension axis is moved to a position at which the longitudinal surface of the pendulum rod is set in a horizontal position. Movement of the suspension axis is carried out



(a)



(b)

Figure 1. Structural scheme of the laboratory installationd (a) structural scheme (b) general view.

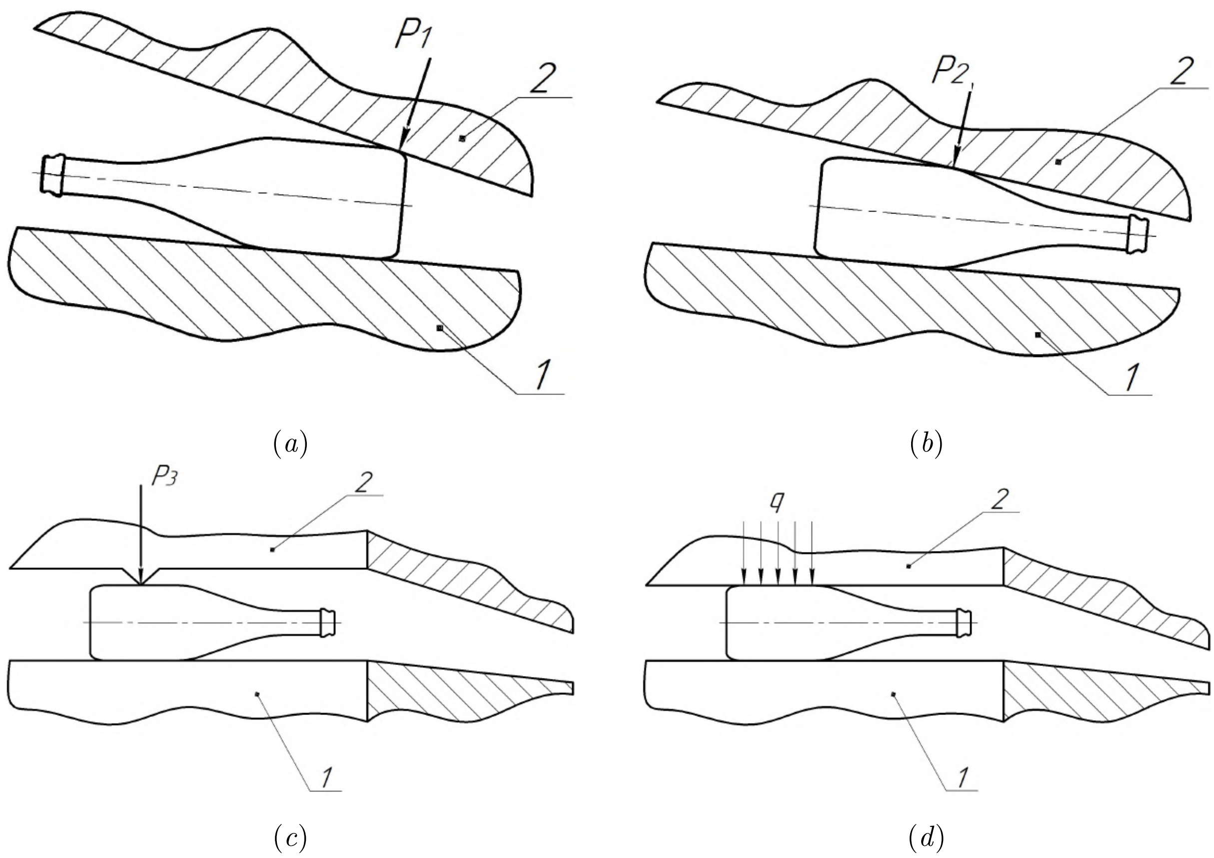


Figure 2. Schemes of the initial contact of the bottle with the working surface of the upper jaw, 1 – lower jaw; 2 – upper jaw.

by means of gaskets 15 (or a screw connection). The horizontal setting of the pendulum rod is controlled by a level (16).

Results of a single impact of a flat impactor on bottles for sparkling wines are given as an example. Impactor mass is 5 kg, drop height is 0.7 m.

The initial application of the load was simulated with different method of feeding the bottle into the inclined crushing chamber of the vibratory jaw crusher. When feeding the bottle into the crushing chamber with the bottom in the direction of the unloading window (figure 2, a), the first impact occurs when the working surface of the upper jaw comes into contact with the ring of strength of the bottle (force P1).The implementation of such a scheme on a pendulum impact tester showed that the bottle is destroyed (figure 3) by a single impact, however more than 50% of the glass breakage has convex shapes, which reduce the filling factor of the transporting container.

When feeding the bottle into the crushing chamber with the neck in the direction of the unloading window (figure 2, b), the first impact occurs when the working surface of the upper jaw comes into contact with the bottle shoulders (force P3). When the impact of the pendulum impact tester interacted with the bottle shoulders, a product with a size of more than 50 mm with a destroyed neck and a whole bottom was mainly formed (figure 4).

The bottle can be loaded into the crushing chamber in a position where the longitudinal axes of symmetry of the bottle and the chamber are perpendicular (figure 2, c, d). When the cylindrical surface is affected by a point load P2 (figure 2, c), with sufficient destruction of the

Figure 3. Impact on the bottom (P1).

Figure 4. Impact on the bottle shoulders (P2).

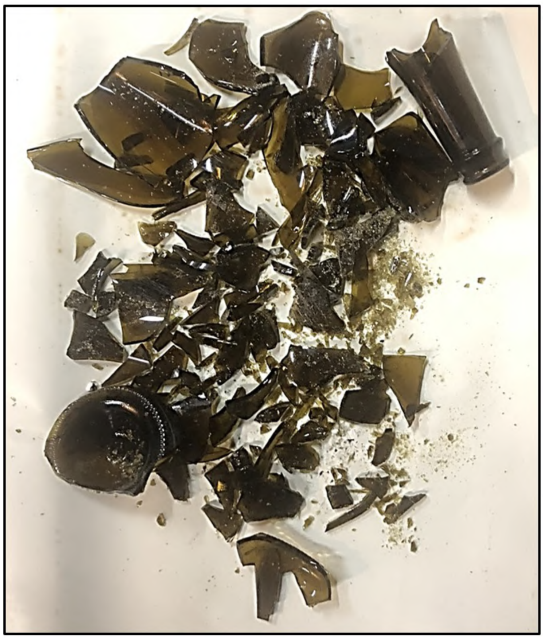


Figure 5. Impact in the middle (P3).

Figure 6. Impact on the plane (q).

cylinder, the neck and bottom are not subjected to destruction (figure 5).

The preferred result is obtained when the surface of the bottle interacts with a distributed load q (figure 6).

The result obtained shows sufficiency of one impact for the effective destruction of a brittle material with internal cavities, which predetermines the need to create small-sized crushing plants. Conversion of bottle convex shapes into a flat state allows you to significantly increase the filling factor of the shipping container and have a high-quality initial product for processing into commercial products.

The experience of using vibratory jaw crushers to obtain fine-grained materials shows the possibility of implementing the results obtained in similar designs [15, 16].

Crushers of this type have a pronounced impact nature of the load applied to crushed materials, as well as the advantages of jaw and rotary crushers. In general terms, the design scheme of vibratory crushers is an oscillatory system with vibrations of 16–32 Hz communicated to the crusher jaws [17, 18].

The material crushing process is effectively controlled in a vibratory jaw crusher with an inclined crushing chamber [19]. The crusher (figure 7) includes a passive (lower) jaw (1) mounted on elastic elements (5) and simultaneously performing the function of the housing. The active jaw (3) is installed in the racks of the passive jaw by means of the suspension axis (2), relative to which it can perform rotational vibrations. Vibrations of the jaws are generated by a two-shaft inertial vibration exciter (4). Destruction of the material crushed occurs in the crushing chamber formed by the working surfaces of the passive jaw (1) and the active jaw (2).

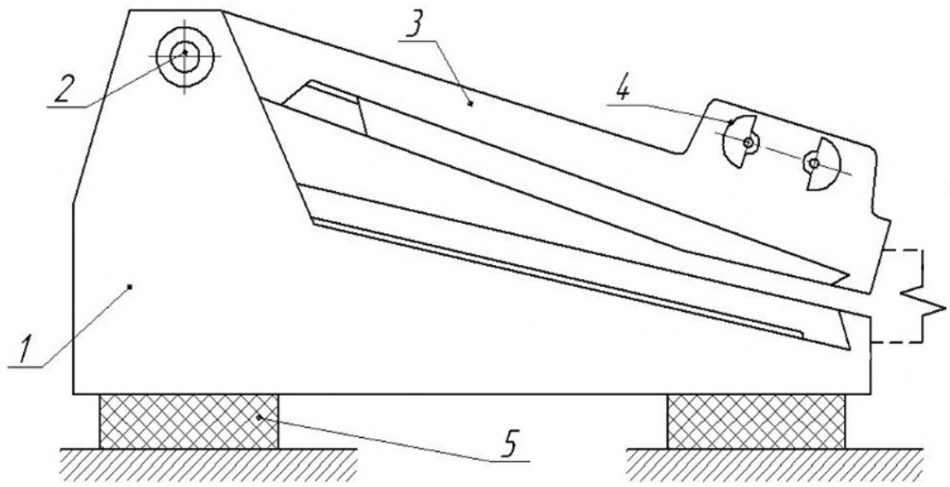


Figure 7. Structural scheme of the vibratory crusher.

Grinding was carried out on a laboratory sample of a vibratory jaw crusher with a large set of adjustable parameters: the frequency and amplitude of oscillations of the jaws, the magnitude and direction of the disturbing force, the weight of the jaws, the size of the unloading gapt, the rigidity of the elastic elements, the profile of the working surface of the jaws, the grip angle, the angle of inclination of the conveying surface. Crushing was carried out on bottles with a cylinder diameter of 90 mm, identical to those studied on a pendulum impact tester. Based on the fact that the width of the crushing chamber of the laboratory sample is less than the height of the bottle, its loading was carried out according to the scheme of figure 2, a.

At the first contact of the bottle with the working surface of the jaw, the process of bottle destruction corresponded to the destruction on the impact tester. Obtained was a high-quality mass of a flat shape suitable to fill the transport container. However, a feature of the crusher is the possibility of producing marketable products. Subsequently, the resulting flat material moved in the crushing chamber to the discharge window, receiving a high-frequency impact. The resulting presentation of fine-grained material from a crushed bottle is shown in figure 8.

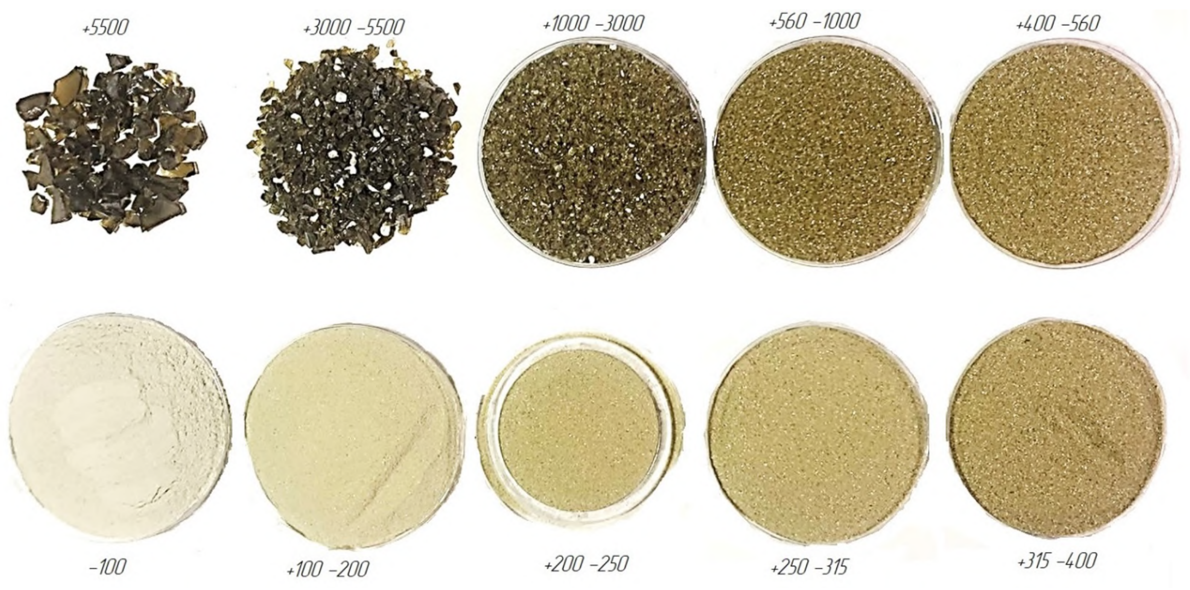


Figure 8. Fine-grained material from a crushed bottle (μm).

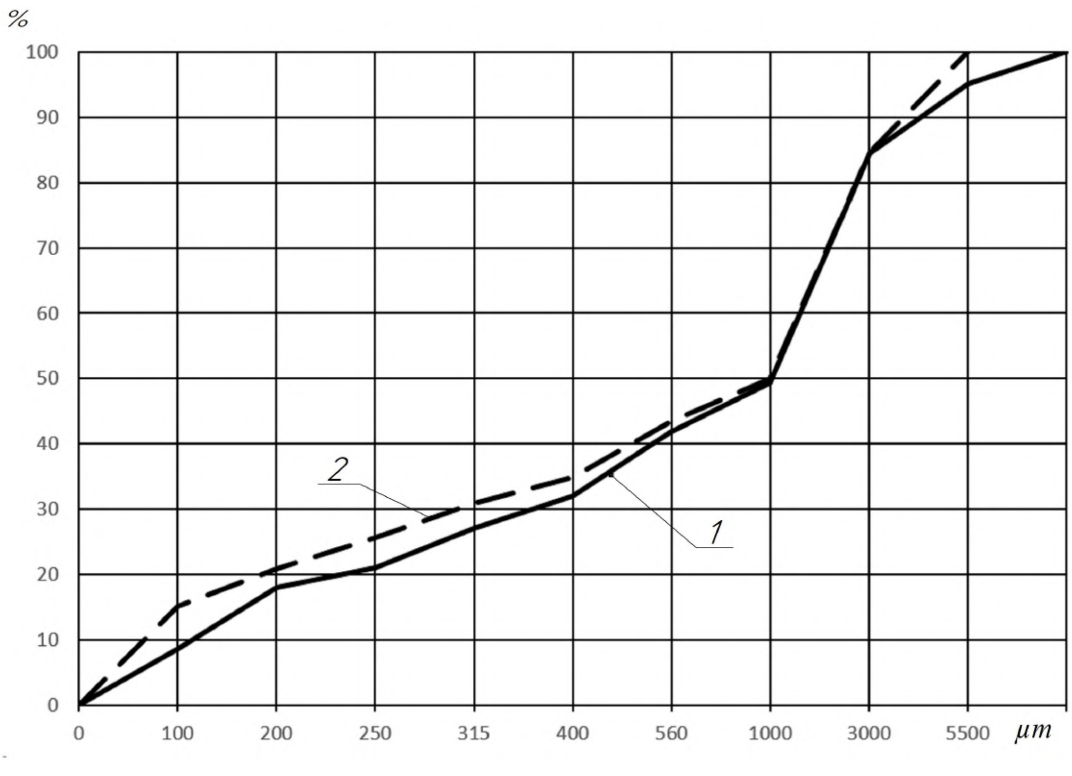


Figure 9. Crushed bottle presentations.

A wide range of adjustable parameters allows you to control the process, create rational crushing modes and obtain the required granulometric composition of the finished product. Figure 9 shows the characteristics of crushed glass at a frequency of jaw oscillations of 17 Hz (curve 1) and 21 Hz (curve 2). The mass of the movable jaw is 97 kg, the width of the crushing chamber is 120 mm, and the length is 550 mm.

As can be seen from the graph, increasing the oscillation frequency to 21 Hz (curve 2) eliminates the +5.5 mm class, narrows the size range of the crushed product and increases the yield of powder material.

3. Conclusion

According to the purpose of the work, the studies carried out on the example of glass container destruction substantiated efficiency of crushing brittle materials in a vibratory jaw crusher with an inclined crushing chamber.

Feeding a cylindrical feedstock with a diameter of 90 mm into the crusher and obtaining a fine-grained product shows the prospects for creating a small-sized vibrating jaw crusher with the implementation of medium, fine crushing and grinding in it, which will significantly reduce the number of units in the production process chain, reduce their cost and expand the range of products obtained fine-grained and powder materials.

A laboratory plant with a horizontal type pendulum impact tester allows you to pre-select the profile of the working surface of the jaws, get a physical picture of the destruction of the material and determine the main dynamic characteristics of the crusher.

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References

[1] Malich N G, Blohin V S and Degtyarev A O 2008 *Mining Information and Analytical Bulletin* (1) 365–380 URL `https://www.giab-online.ru/files/Data/2008/1/42a__Malich21.pdf`
[2] Guryanov G A and Baigereyev S R 2017 *Vestnik Vostochno-Kazahstanskogo tehnicheskogo universiteta im. D. Serikbaeva [Bulletin of the East Kazakhstan Technical University named after D. Serikbaeva]* (2) 52–57 URL `https://www.ektu.kz/files/vestnik/vestnik_2-2017.pdf`
[3] African Pegmatite 2020 Use of Glass Powders in Industrial Settings: A Short Overview URL `https://mineralmilling.com/use-of-glass-powder-in-industrial-settings/`
[4] Deng Y, Yan C, Zhang J, Yin L, Liu S and Yan Y 2022 *Journal of Cleaner Production* **333** 130222 ISSN 0959-6526 URL `https://doi.org/10.1016/j.jclepro.2021.130222`
[5] Souza A C, Pereira M F and Mossin L C 2021 *Journal of Materials Research and Technology* **12** 1794–1803 ISSN 2238-7854 URL `https://doi.org/10.1016/j.jmrt.2021.03.099`
[6] Jiang Y, Ling T C, Mo K H and Shi C 2019 *Journal of Environmental Management* **242** 440–449 ISSN 0301-4797 URL `https://doi.org/10.1016/j.jenvman.2019.04.098`
[7] Tahwia A M, Essam A, Tayeh B A and Elrahman M A 2022 *Case Studies in Construction Materials* **17** e01648 ISSN 2214-5095 URL `https://doi.org/10.1016/j.cscm.2022.e01648`
[8] Peng L, Zhao Y, Ban J, Wang Y, Shen P, Lu J X and Poon C S 2023 *Cement and Concrete Composites* **137** 104909 ISSN 0958-9465 URL `https://doi.org/10.1016/j.cemconcomp.2022.104909`
[9] Kazymyrenko Y O, Drozd O V and Zharskiy Y V 2020 *Vcheni zapysky TNU imeni V.I. Vernadskoho. Seriia: Tekhnichni nauky* **31 (70)**(4) 180–185 URL `http://www.tech.vernadskyjournals.in.ua/journals/2020/4_2020/27.pdf`
[10] Meyer C 2001 Recycled Glass - From Waste Material to Valuable Resource *Recycling and Reuse of Glass Cullet: Proceedings of the the International Symposium organised by the Concrete Technology Unit and held at the University of Dundee, Scotland, UK on 19 - 20 March 2021* ed Dhir R K, Limbachiya M C and Dyer T D (Thomas Telford) pp 1–10 URL `https://doi.org/10.1680/rarogc.29941.0001`
[11] Mutafela R N, Mantero J, Jani Y, Thomas R, Holm E and Hogland W 2020 *Chemosphere* **241** 124964 ISSN 0045-6535 URL `https://doi.org/10.1016/j.chemosphere.2019.124964`

[12] Shelby J E 2005 *Introduction to Glass Science and Technology* 2nd ed (Cambridge: Royal Society of Chemistry) ISBN 9781839162398 URL https://belglas.files.wordpress.com/2021/01/shelbyj.e.introductiontoglassscienceandtechnology2nded.rsc20050854046399.pdf
[13] Musgraves J D, Hu J and Calvez L (eds) 2019 *Springer Handbook of Glass* Springer Handbooks (Cham: Springer) ISBN 9783319937267 URL https://doi.org/10.1007/978-3-319-93728-1
[14] Soloshenko L 2006 *Podatky ta buhgalterskyi oblik* (38) 28 URL https://zakon.rada.gov.ua/rada/show/n0014697-06#Text
[15] Wolny S 2013 *Archives of Metallurgy and Materials* **58** URL https://doi.org/10.2478/amm-2013-0092
[16] Mazur M 2017 Possible applications of vibratory technology in crushing technological lines *17 International Multidisciplinary Scientific GeoConference* vol 11 (Bulgaria: SGEM) pp 965–972 URL https://www.proquest.com/openview/b72e216333701fe683556d84ba0cab58/1?pq-origsite=gscholar&cbl=1536338
[17] Shokhin A E 2020 *Journal of Machinery Manufacture and Reliability* **49**(6) 500–510 ISSN 1934-9394 URL https://doi.org/10.3103/S1052618820060084
[18] Altshul G M, Gouskov A M and Panovko G Y 2021 *Journal of Machinery Manufacture and Reliability* **50**(1) 26–33 ISSN 1934-9394 URL https://doi.org/10.3103/S1052618821010052
[19] Fedoskina O V, Franchuk V P, Fedoskin V O and Haddad J S 2022 *Geo-Technical Mechanics* **161** 66–74

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Study of the impact of the open pit productivity on the economic indicators of mining development

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Study of the impact of the open pit productivity on the economic indicators of mining development

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Abstract. The article studied the issue of improving the scientific and methodological base in the field of design and planning of open-pit mining by developing new and adjusting existing methods for determining the ore productivity of an open-pit, which should take into account the interconnection between the mining schedule and the productivity of an open -pit for ore, based on the condition for ensuring the standard volume of finished to the extraction of reserves. When choosing the production of an open-pit for ore, it is necessary to take into account the impact of the interconnection between the schedule of mining and production, based on the conditions of regulatory regulation of the volume of mining for the excavation of reserves, on the cost of ore mining and concentrate production. With an increase in ore productivity, the cost of ore mining, as well as the cost of production of concentrate reduction. At the same time, the very possible productivity of the open-pit for especially minerals is achieved, the economic efficiency of the development of deposits is achieved with the chosen direction of the open -pit. A decrease in productivity for a common mineral by 20 and 40% entails a decrease in profit from the development of the deposit by 10 and 20%, respectively. It has been determined that an increase in the slope angle of the working side of the open-pit significantly reduces the economic efficiency of the development of the deposit due to the fact that the operation of the open -pit with a large slope angle entails not only a decrease in the current stripping ratios as a result of an improvement in the mining schedule, but also a decrease in ore productivity, which reduces the present value of marketable products due to an increase in the period of development of the deposit. The results of the studies performed can be used by design organizations and mining enterprises in determining the ore productivity of an open-pit.

1. Introduction

To select the productivity of a open-pit, which ensures the maximum efficiency of field development, a comprehensive technical and economic analysis of the operation of the enterprise is required [1–3], taking into account, among other things [4, 5], the influence of the time factor on the evaluation of the results of its work [6, 7].

The existing relationship between the parameters of the development system [8, 9], which provide the norm of reserves ready for excavation in a open-pit [10, 11], determines, with a change in productivity for a mineral, a change in stripping ratios [12–14]. In turn, the change in stripping ratio is reflected in the volumes of rock mass and their distribution over the years of operation, which ultimately is one of the main factors affecting the economic indicators of a open-pit mine [15–17]. At the same time, the maximum productivity for ore also determines the maximum or close to maximum productivity for the rock mass, which leads to an increase in the cost of developing the deposit. Thus, an increase in the productivity of a open-pit for a mineral is accompanied by an increase not only in income, but also in costs [18, 19].

In this regard, the question arises whether there will be profitability in terms of economic efficiency [20–22] of operating a open-pit with the maximum possible productivity for a mineral [23, 24].

2. Object and methods of research

Most studies aimed at establishing the impact of open-pit productivity on the economic indicators of development, the existing relationship between the development of mining and mining operations in a open-pit [25–27], is considered only on the basis of the condition that a change in the angle of slope of the working side of the open-pit [28] leads to a change in the current stripping ratios [29–31]. This does not take into account the need to ensure the standard volume of reserves ready for extraction [32–34].

It is known that as the production capacity of a open-pit increases and its lifetime decreases, with the same reserves, the specific semi-fixed costs change [35], which means that the cost of ore mining also changes [36]. Therefore, it is necessary to investigate the change in the cost of ore mining and the production of final marketable products, taking into account changes in stripping ratios with an increase in ore productivity.

Therefore, the goal was set: to improve the scientific and methodological base in the field of design and planning of open pit mining by developing new and corrections existing methods for determining the productivity of a open-pit by ore, which should take into account the interconnection between the mining mode and the productivity of a open-pit by ore, based on the condition for ensuring the standard volume stocks ready for extraction.

3. Results

The creation of normal working conditions for a open-pit for various ore productivity options, within the maximum possible value, is possible by changing the width of working benches [37,38], which ensures the standard of reserves ready for excavation. At the same time, an increase in the width of working benches leads to a decrease in the number of working benches within the deposit and, accordingly, to a change in the length of the mining front, both in ore horizons and in overburden, which largely determines the distance of transporting the rock mass in the open-pit. With an increase in the width of the working bench, the transportation distance increases both on ore horizons and on overburden. This is due to the fact that with an increase in the width of the working bench, the ore front is concentrated on a smaller number of benches in the lower part of the open pit. At the same time, the overburden front of mining operations increases due to an increase in the number of underlying overburden benches. Therefore, when determining the cost of ore mining and the production of final marketable products, it must be taken into account that with an increase in ore productivity, the width of working benches will increase, as well as the haulage arm from the faces to the opening working. Therefore, even a small increase in the distance of transportation with significant volumes of traffic will lead to a significant increase in costs.

For conditions close to the mining and processing plants of Krivbass, let us analyze the impact of the productivity of an open-pit on the cost of production of the final marketable product. We investigate the work of an open-pit developing a steeply dipping mineral deposit. Let's divide the open-pit field by depth into zones, within which the pattern of changes in the volume of rock mass with a decrease in mining operations remains constant.

The studies carried out allow us to establish the measure of the influence of various costs on the production cost of the concentrate when changing the productivity of the open pit for ore.

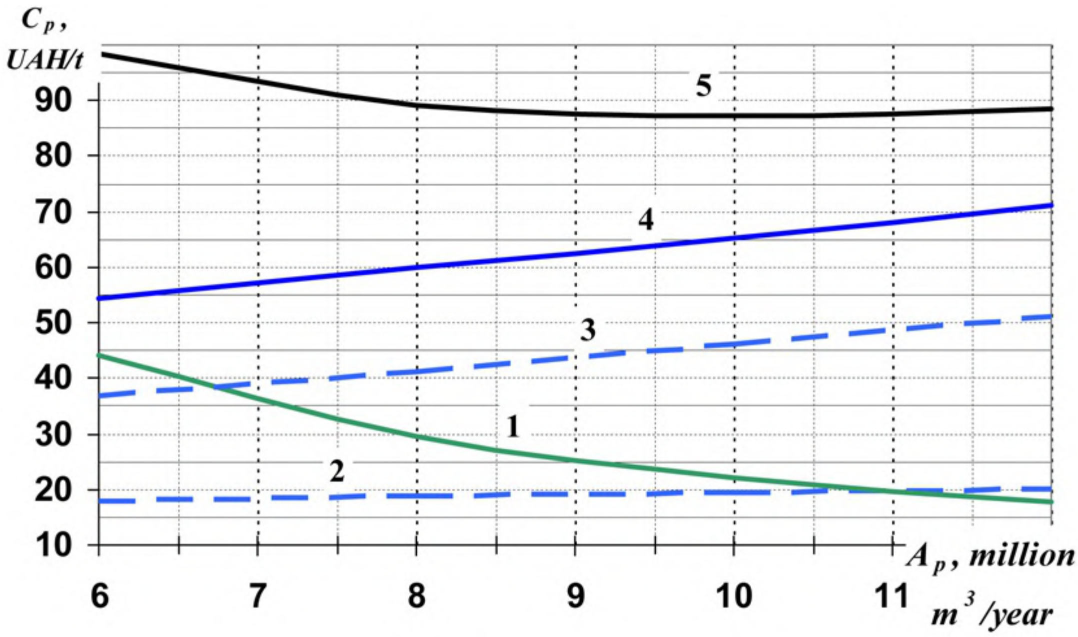

Figure 1. Influence of open pit productivity in terms of ore on the production cost of ore mining and its components at the first stage of its operation: 1 – unit semi-fixed costs for ore mining; 2 – unit conditionally variable costs for ore mining without overburden costs; 3 – unit conditionally variable costs for the excavation of overburden; 4 – unit conditionally variable costs for ore mining; 5 – unit production cost of ore.

From figure 1 and figure 2, it can be seen that the unit semi-fixed costs for ore mining (line 1) are the same in both the first and second periods and decrease with an increase in ore productivity.

However, in the second period, due to a decrease in stripping ratios, the specific conditionally variable costs for ore mining with an increase in productivity slightly decrease (line 4, figure 2).

Curve 5 (figure 2, figure 2) shows the change in the production cost of ore depending on the ore productivity of the open pit with the already chosen direction of development of mining operations and indicates the presence of an optimal productivity value. On figure 3 shows the change in the cost of production of concentrate from the productivity of an open-pit for ore for the first (line 1) and second (line 2) periods of work. It can be seen from the figures that with an increase in ore productivity, the cost of ore mining, as well as the cost of concentrate production, decrease.

However, the cost cannot fully characterize the increase in production for which development is being carried out. The main purpose of the enterprise is to make a profit. Therefore, it is more rational to solve the problem of determining the optimal productivity of an open-pit based on the profit from the sale of commercial products of the mining and processing plant. Profit from the sale of marketable products (concentrate) was taken as an optimality criterion when comparing options. For the commensurability of costs and incomes at different times, they were brought to one moment of evaluation.

We calculate the costs and revenues from the development of a mineral deposit and the production of a concentrate when operating an open-pit with different productivity values and a price for a concentrate, while for each performance option we set certain rates of deepening of mining operations. At the same time, when changing the ore productivity of an open-pit, it is necessary to take into account a change in the angle of slope of the working side of the

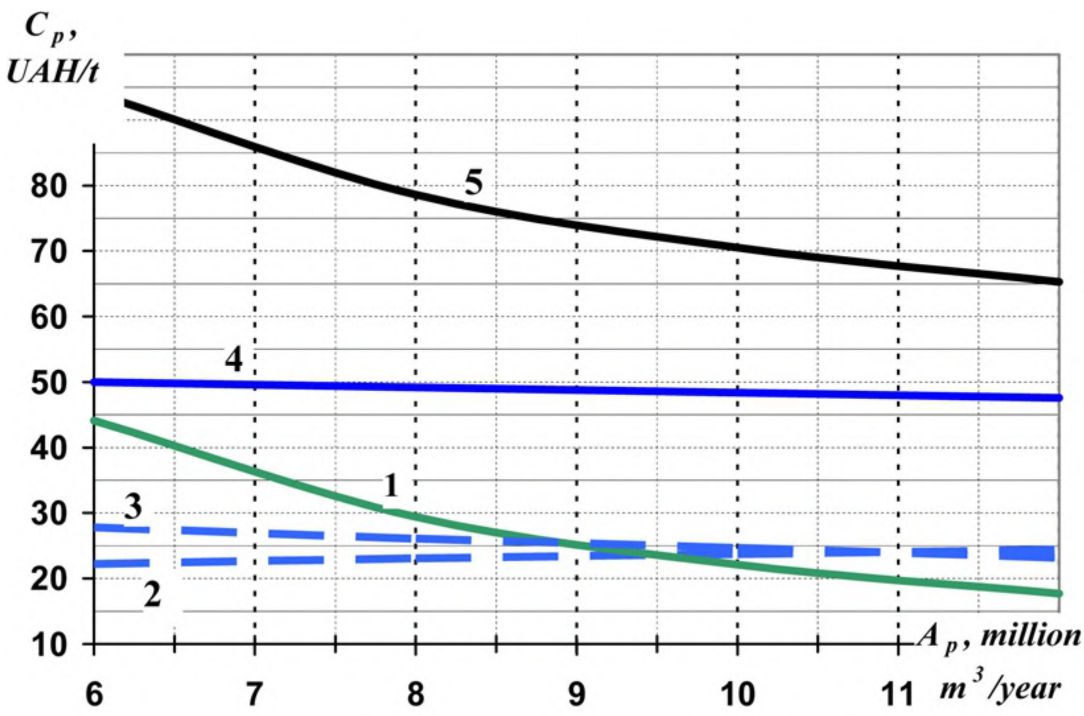

Figure 2. Influence of open pit ore productivity on the production cost of ore mining and its components at the second stage of its operation: 1 – unit semi-fixed costs for ore mining; 2 – unit conditionally variable costs for ore mining without overburden costs; 3 - unit conditionally variable costs for the excavation of overburden; 4 – unit conditionally variable costs for ore mining; 5 – unit production cost of ore.

open-pit due to changes in the parameters of the development system that ensure the standard of reserves ready for excavation in the open-pit. That leads to a change in the stripping ratios and the distance of transportation of the rock mass.

These calculations are made for a certain variant of the development of mining operations in an open-pit and only indicate the presence of optimal productivity. A change in the direction of development of mining operations entails a change in the calendar distribution of the volumes of overburden and mining operations.

The calculation results are shown in figure 4. From the graphs of the function $K=f(A_p)$, $C_o=f(A_p)$ it can be seen that the given total capital (K) and operating (C_o) costs increase with the increase in the production capacity of the open pit.

The curve $PR_p=f(A_p)$, which characterizes the change in the reduced profit depending on the productivity of the open pit, shows that the maximum possible productivity of the open pit for minerals ensures the maximum economic efficiency of the development of the deposit in the chosen direction of the deepening of the open pit. In this case, the maximum profit is provided with a productivity of 12 million m^3/year. A decrease in productivity for minerals by 20 and 40% entails a decrease in profit from the development of the deposit by 10 and 20%, respectively.

On figure 5 shows the influence of the slope angle of the working side of the open pit on the reduced profit from the development of the deposit when the norm of reserves ready for excavation is provided in the open pit. It can be seen from the graph that an increase in the slope angle of the working side significantly reduces the economic efficiency of field development. This is explained by the fa ct that the operation of an open-pit with a large slope angle of the working side entails a decrease in productivity not only for waste rocks, but also for ore, which

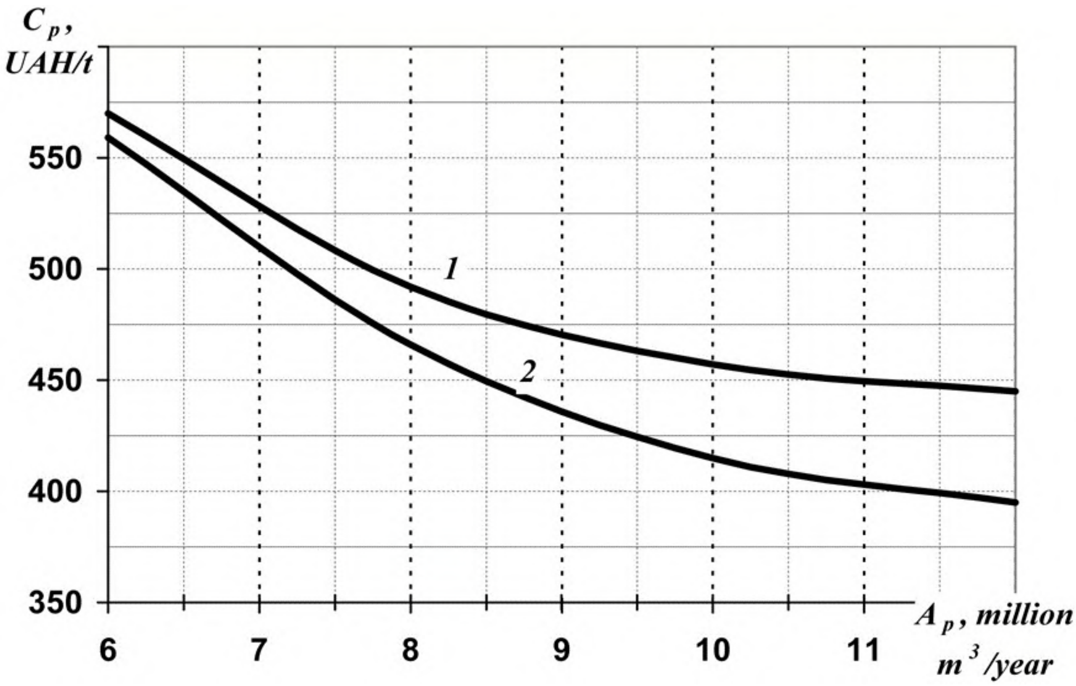

Figure 3. Influence of open pit ore productivity on the production cost of the concentrate at the first (1) and second (2) stages of open pit operation.

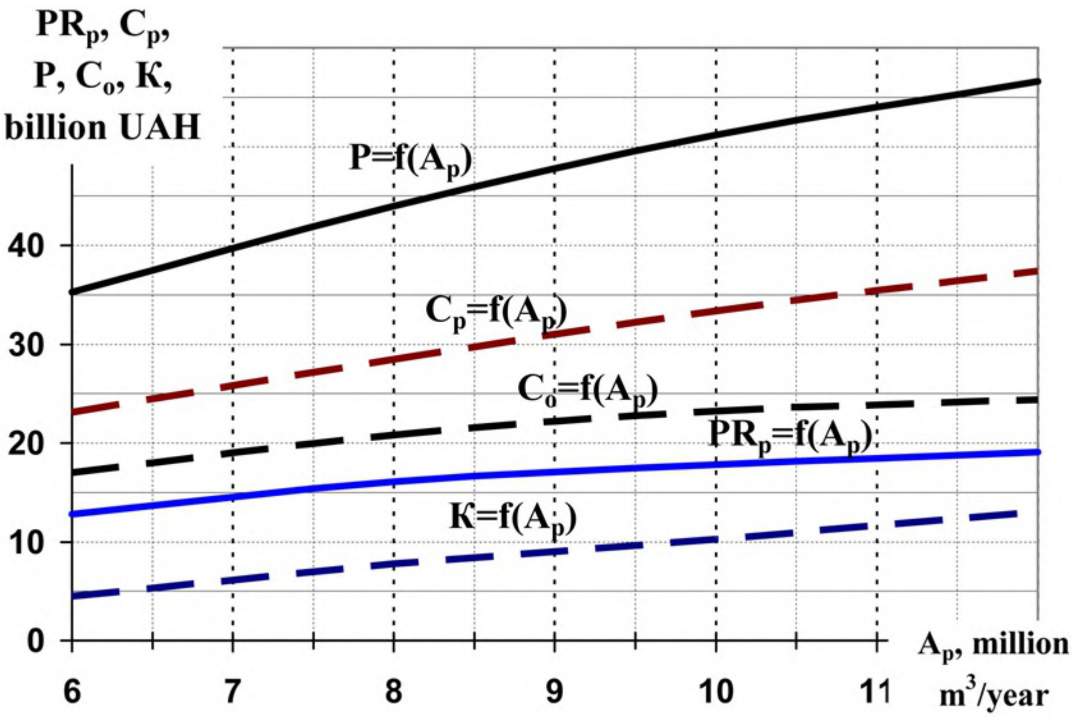

Figure 4. Change in costs and income from the development of a mineral deposit and the production of a concentrate, depending on the ore productivity of an open-pit.

Figure 5. Graph of changes in profit from the development of the field, depending on the angle of slope of the working side of the open pit.

reduces the present value of marketable products due to an increase in the development period of the deposit.

4. Conclusions

An increase in the slope angle of the working side significantly reduces the economic efficiency of the development of the deposit due to the fact that the operation of an open-pit with a large angle of slope entails not only a decrease in the current stripping ratios as a result of a change in the mining schedule, but also a decrease in ore productivity, which reduces the present value of marketable products due to an increase in the period of development of the field.

The maximum possible productivity of an open-pit in terms of minerals ensures the maximum economic efficiency of the development of a deposit in the chosen direction of deepening the open-pit. A decrease in productivity for minerals by 20 and 40% of the maximum value entails a decrease in profit from the development of the deposit by 10 and 20%, respectively.

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References

[1] Selyukov A, Gerasimov A and Grishin V 2020 *E3S Web of Conferences* **174** 01020 URL https://doi.org/10.1051/e3sconf/202017401020

[2] Bazaluk O, Petlovanyi M, Zubko S, Lozynskyi V and Sai K 2021 *Minerals* **11**(1) 858 URL https://doi.org/10.3390/min11080858
[3] Pysmenniy S, Shvager N, Shepel O, Kovbyk K and Dolgikh O 2020 *E3S Web of Conferences* **166** 02006 URL https://doi.org/10.1051/e3sconf/202016602006
[4] Romanenko A, Bilenko A, Tereschenko V and Pshenichnyiy V 2012 *Girnichiy visnik KNU* **95**(1) 25–31
[5] Lutsenko A 2017 *Quality – Access to Success* **18**(S1) 226–230 URL https://www.proquest.com/openview/87ac497268d7644e316b4c1bfc24d289/1.pdf?pq-origsite=gscholar&cbl=1046413
[6] Kosolapov A and Ptashnik A 2011 *Mezhdunarodnyiy zhurnal prikladnyih i fundamentalnyih issledovaniy* **6** 33–36
[7] Zykov P, Zvarych E, Karasev A and Weber D 2017 *E3S Web of Conferences* **134** 01006 URL https://doi.org/10.1051/e3sconf/201913401006
[8] Sobko B Y, Lozhnikov O V, Chebanov M O and Kardash V A 2021 *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu* (4) 23–28 URL https://doi.org/10.33271/nvngu/2021-4/023
[9] Babets Y K, Bielov O P, Shustov O O, Barna T V and Adamchuk A A 2019 *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu* (6) 36–44 URL https://doi.org/10.29202/nvngu/2019-6/6
[10] Pysmennyi S, Fedko M, Shvaher N and Chukharev S 2020 *E3S Web of Conferences* **201** 01022 URL https://doi.org/10.1051/e3sconf/202020101022
[11] Selyukov A, Gerasimov A and Byrdin K 2019 *E3S Web of Conferences* **105** 01047 URL https://doi.org/10.1051/e3sconf/201910501047
[12] Joukov S, Lutsenko S, Hryhoriev Y, Martyniuk M and Peregudov V 2020 *E3S Web of Conferences* **166** 02005 URL https://doi.org/10.1051/e3sconf/202016602005
[13] Moldabayev S, Rysbaiuly B, Sultanbekova Z and Sarybayev N 2019 *E3S Web of Conferences* **123** 01049 URL https://doi.org/10.1051/e3sconf/201912301049
[14] Selyukov A and Rybár R 2019 *E3S Web of Conferences* **105** 01043 URL https://doi.org/10.1051/e3sconf/201910501043
[15] Shpanskiy O V, Ligotskiy D N and Borisov D V (eds) 2004 *Proektirovanie proizvodstvennoy moschnosti karerov* (Sankt–Peterburg: Sankt–Peterburgskiy gosudarstvennyiy gornyiy institut)
[16] Dryzhenko A, Shustov A and Moldabayev S 2017 Justification of parameters of building inclined trenches using belt conveyors *17th International Multidisciplinary Scientific GeoConference SGEM 2017, 43 June - 5 July, 2017* pp 471–478 URL https://www.sgem.org/index.php/elibrary-research-areas?view=publication&task=show&id=2653
[17] Dryzhenko A, Moldabayev S, Shustov A, Adamchuk A and Sarybayev N 2017 Open pit mining technology of steeply dipping mineral occurences by steeply inclined sublayers *17th International Multidisciplinary Scientific GeoConference SGEM 2017, 43 June - 5 July, 2017* pp 599–605 URL https://doi.org/10.5593/sgem2017/13/S03.076
[18] Shustov O O, Bielov O P, Perkova T I and Adamchuk A A 2018 *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu* (3) 5–18 URL https://doi.org/10.29202/nvngu/2018-3/6
[19] Bielov O, Shustov O, Adamchuk A and Hladun O 2018 *Solid State Phenomena* **277** 251–268 URL https://doi.org/10.4028/www.scientific.net/SSP.277.251
[20] Pysmennyi S, Peremetchyk A, Chukharev S, Fedorenko S, Anastasov D and Tomiczek K 2022 *IOP Conference Series: Earth and Environmental Science* **1049**(1) 012029 URL https://doi.org/10.1088/1755-1315/1049/1/012029
[21] Kalinichenko V, Dolgikh O, Dolgikh L and Pysmennyi S 2020 *Mining of Mineral Deposits* **14**(4) 31–39 URL https://doi.org/10.33271/mining14.04.031
[22] Moshynskyi V S, Korniienko V Y, Malanchuk Y Z, Khrystyuk A O, Lozynskyi V H and Cabana E C 2021 *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu* (6) 35–41 URL https://doi.org/10.33271/nvngu/2021-6/035
[23] Malanchuk Z, Korniyenko V, Malanchuk Y, Khrystyuk A and Kozyar M 2020 *E3S Web of Conferences* **166** 02008 URL https://doi.org/10.1051/e3sconf/202016602008
[24] Malanchuk Y, Korniienko V, Moshynskyi V, Soroka V, Khrystyuk A and Malanchuk Z 2019 *Mining of Mineral Deposits* **13**(1) 49–57 URL https://doi.org/10.33271/mining13.01.049
[25] Rzhevskiy V V, Novozhilov M G and Yumatov B P (eds) 1971 *Nauchnyie osnovyi proektirovaniya karerov* (Moscow: Nedra)
[26] Arsentev A I (ed) 2002 *Proizvoditelnost karerov* (Sankt-Peterburg: Sankt-Peterburgskiy gornyiy institut)
[27] Polischuk A K, Bliznyukov V G and Rudenko A I 1968 *Razrabotka rudnyih mestorozhdeniy* **5** 23–26
[28] Imashev A, Suimbayeva A, Zhunusbekova G, Zeitinova S, Kuttybayev A and Mussin A 2022 *Mining of Mineral Deposits* **16**(3) 61–66 URL https://doi.org/10.33271/mining16.03.061
[29] Anistratov Y I and Anistratov K Y (eds) 2002 *Proektirovanie karerov* (Moscow: Izdatelstvo NPK Gemos Limited)

[30] Sokolovskiy A V 2007 *Gorn. inf.-analit. Byull.* **12** 21–26
[31] Arsentev A I 2008 *Gornyiy zhurnal* **11** 54–58
[32] Azarian V, Lutsenko S, Zhukov S, Skachkov A, Zaiarskyi R and Titov D 2020 *Mining of Mineral Deposits* **14**(1) 1–10 URL `https://doi.org/10.33271/mining14.01.001`
[33] Blizniukov V H 2017 *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu* **1** 44–49
[34] Shustov O O, Pavlychenko A V, Bielov O P, Adamchuk A A and Borysovska O O 2021 *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu* **5** 30–36 URL `https://doi.org/10.33271/nvngu/2021-5/030`
[35] Bolatova A, Kuttybayev A, Kainazarov A, Hryhoriev Y and Lutsenko S 2020 *News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences* **1** 33–38 URL `https://doi.org/10.32014/2022.2518-170X.137`
[36] Shestakov V A (ed) 2003 *Proektirovanie gornyih predpriyatiy* (Moscow: MGU)
[37] Tyukov P O and Loginov E V 2021 *E3S Web of Conferences* **266** 04014 URL `https://doi.org/10.1051/e3sconf/202126604014`
[38] Plotnikov E, Kolesnikov V, Šimková Z and Demirel N 2020 *E3S Web of Conferences* **174** 01003 URL `https://doi.org/10.1051/e3sconf/202017401003`

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Study of hydroerosion process parameters of zeolite-smectite tuffs and underlying rock

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Study of hydroerosion process parameters of zeolite-smectite tuffs and underlying rock

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Abstract. The paper considers the expediency of complex processing of zeolite-smectite tuffs using the method of borehole hydro-mining. The basic information about deposits of zeolite-smectite tuffs in the Rivne-Volyn region of Ukraine and the main areas of their application in industry are presented. Also, the method of calculating the parameters of the process of hydraulic erosion of tuffs and underlying rocks by the method of borehole hydro-mining is given, and the dependence of the specific consumption of the working agent during erosion of tuffs and underlying rocks on the diameter of the nozzle at variable pressure is presented. The dependences for determining the rational forms of recess chambers with the specified erosion radius are given.

1. Features of occurrence of zeolite-smectite tuffs in the Rivne-Volyn region

At the current stage of development of mining science, intensive research and industrial development of Ukraine's raw resources are being carried out [1–5]. The Rivne-Volyn region of Ukraine is rich in deposits of zeolite-smectite tuffs, which are of great interest to the industry of Ukraine. Currently, their industrial extraction is not carried out, however, in the development of basalt deposits, in particular (Berestovetske deposit, Ivano-Dolynsk basalt deposit (Rivnen district), Rafaliv basalt deposit (Varas district)), tuffs are the host rock, and, as a rule, when loading the blasted basalt mass for processing tuffs are sent to the dump [6–9].

Tuff deposits are known in Iceland, Italy, New Zealand, Azerbaijan (Gyuzdek, Garadag district), USA (Yellowstone National Park).

Those tuffs that have low sound and thermal conductivity are loose and porous. Calcareous tuffs are used as building materials, floor and facing tiles are made from travertine. Calcareous tuff is used for the construction of buildings as a light building stone, thermal insulation material, for the production of lime.

At the same time, the zeolite-smect tuffs of these deposits deserve special attention and study. Their use in the national economy is already widely known as a feed supplement for animals and poultry, to increase soil fertility and their deactivation in radioactively contaminated soils, and wastewater treatment. In construction, tuffs are used to make bricks, roof tiles, ceramic tiles, and as a pigment for paints. Zeolites have valuable physical and mechanical properties, in particular, resistance to aggressive environments and ionizing radiation, reversible

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low-temperature dehydration, high mechanical strength, absence of toxic compounds and contamination by microorganisms, the ability to readsorb water, gaseous tuffs are prone to easy ion exchange of cations at normal temperature and pressure [10, 11].

According to the forecasts of geologists of the Rivne expedition, the tuff resources of the Rivne region amount to hundreds millions of tons and lie along the western flank of the Poliska saddle and the western slope of the Ukrainian crystalline shield in the form of a strip 1...10 km wide at depths 5...200 m. On the territory of the Rivne region, in particular, the Rafaliv basalt deposit (figure 1), tuffs lie at a depth 4...60 m and are stretched in the form of a strip from north to south.

Figure 1. The Rafaliv deposit near the villages of Polytsi and Ivancha, Rivne region (taken from open sources).

The mineralogical and petrographic characteristics of these tuffs, their mineral composition (table 1), structural features have been studied in sufficient detail [12–14], which allows them to be used purposefully and effectively.

Complex processing of zeolite-smectite tuffs should be carried out in two ways: well hydraulic production and quarrying. The mine method is not considered due to the high cost of works, difficult mining and geological conditions, high level of groundwater [15, 16].

2. Development of a methodology for calculating the parameters of the hydroerosion process of tuffs and underlying rocks by the method of borehole hydro-mining

The influence of well-known laws of mechanics is manifested in the conditions of borehole hydro-mining (BHM). They are expressed in the manifestation of the balance law of mining pressure work, the results of which, in the conditions of hydraulic mining, are proportional to the loss of minerals in the subsoil [17]. Based on this, the main task of mountain pressure management is to maximize the share of work that goes to the safe deformation of the massif outside the excavation chambers, and to minimize it – to the deformation of the roof and protective units. The specifics

Table 1. Content of elements in tuff samples at different quarries, concentration, %.

The name of the elements	Rafaliv quarry	Berestovtsk quarry	Ivano-Dolynsk quarry
Aluminum	0.03	10.2	3.0
Silicon	30...32	57.2	42.0
Phosphorus	0.1	0	0.15
Sulfur	1,2	0.3	0
Potassium	1.3	2.4	4.8
Calcium	6.4...12.1	15	37.5
Titanium	2.8...4.0	1.3	0.5
Chrome	0.2	0.05	0.1
Manganese	0.070	0.12	0.07
Iron	48...50	12.8	7.0
Nickel	0.2	0.1	0.01
Copper	0.4...0.7	0.17	0.6...1.0
Zinc	0.05	1,2	0.07
Strontium	0.07...0.1	0.07	0.07

of field testing and development by these methods is to conduct excavation chambers without fastening. Continuous extraction of chambers followed by collapse is rational [18, 19]. In the process of excavation, an unloading zone is formed in the roof of the chambers, which perceives only the mass of the roof directly, the pressure of which is mainly transmitted to adjacent massifs and collapsed rocks of the produced space [19–21]. Using this solution, it is possible to reduce the pressure of the roof on the security cells by up to 10%.

For systems with different shapes of recess chambers, the limit erosion radius R is set as a function of the limit span of the roof:

- for a round chamber
$$R = \frac{L}{2}, \tag{1}$$
- for a rhomboid chamber
$$R = \frac{L}{\sin\alpha}, \tag{2}$$
- for a square camera
$$R = \frac{L}{\sqrt{2}}, \tag{3}$$

  where L – the ultimate length of the jet, m; α – the angle of inclination of the jet to the horizon, °.

The most rational parameters $R = f(L)$ there are systems with round and square chambers in which $R \leq L$. Magnification $R > L$ (systems with rhomboid chambers) leads to a significant increase in the consumption of the useful component on the bottoms of the chambers:

$$R = \frac{3.9dH^{0.526}}{8.02 + 4.34 \cdot 10^{-2}dH^{0.843}}, \tag{4}$$

where R – the radius of tuffs erosion in the chamber, m; d – nozzle diameter, m; H – the pressure of the working agent (WA) in the nozzle, Pa.

Checking the axial dynamic pressure of the jet at the distance of the washout radius is carried out according to the equation:

$$P = H\left(\frac{l}{R}\right)^{t}, \tag{5}$$

where P – axial dynamic jet pressure, Pa; l – the length of the initial section of the jet, m; t – the indicator, which for a camera at a distance of 5…7 m, is recommended to be equal to 0.25 m.

The productivity of erosion of tuffs P is determined from the equation:

$$P = K\left(\frac{65.39H^{1.8}}{0.313dH^{-0.5}}\right)e^{0.101dH^{-0.4}}, \tag{6}$$

where K – the coefficient that takes into account the strength properties of rocks, K = 0.0356...0.042; e – the base of the natural logarithm.

The specific consumption of the working agent (WA) and the energy consumption during washing of tuffs:

$$Q = a + bd + cd, \tag{7}$$

where a, b, c – constant approximations, the values of which are given in the table 2.

Table 2. Value of constant approximations.

The pressure of WA before the nozzle, MPa	Constant approximations					
	Searched expense			Energy consumption		
	a	b	c	a	b	c
1.0	-0.5	0.652	-0.014	-1.0	0.240	-0.005
1.6	-1.5	0.415	-0.007	-1.6	0.271	-0.005
2.2	-1.8	0.367	-0.006	-1.2	0.227	-0.004

In figure 2 the dependences of the specific consumption of the WA when washing tuffs on the diameter of the nozzle at variable pressure in the range of 1…2.2 MPa are presented. As a result, we can draw a conclusion about the linear dependence of these parameters.

The erosion radius of the underlying rocks R_1 is calculated according to empirical relationships:

$$R_1 = \frac{10.2H}{1.88 - 4.2\cdot 10^{-2}d + 12.85d^{-1.24}Hd^{-1.24}}. \tag{8}$$

Erosion productivity of underlying rocks P_1:

$$P_1 = 6.36\cdot 10^{-3}d^{3.2}H^{0.725}l_1^{\frac{d-2.66}{200.72H^{0.3}}} + 1.21\cdot 10^{-2}d^2H, \tag{9}$$

where l_1 – the distance of the nozzle to the hole, m.

The specific consumption of the WA for erosion of the underlying rocks is equal to:

$$q = akH^b + c, \tag{10}$$

where a, b, k, c – constant approximations, the values of which are presented in the table 3.

The specific energy capacity of erosion of the underlying rocks E is equal to:

$$E = 1.835\frac{l}{d} + 0.3837H^{0,7} \tag{11}$$

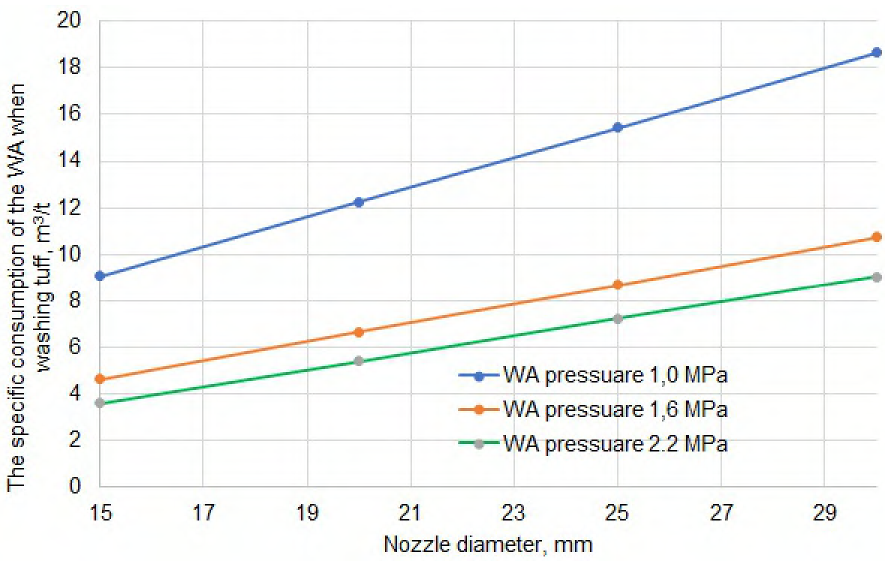

Figure 2. Dependencies of the specific consumption of the WA when washing tuff on the diameter of the nozzle at variable pressure.

Table 3. Value of constant approximations.

Nozzle diameter, d, mm	Constant approximations a	k	b	c
15	99.3	0.0536	-1.26	0.77
20	111.5	0.03216	-1.48	1.16
25	173.3	0.01426	-1.83	1.47
30	252.6	0.05134	-2.27	1.87

According to the results of research in figure 3 the dependences of the specific consumption of WA during washing of the underlying rocks on the diameter of the nozzle at variable pressure in the range of 1...2.2 MPa are presented.

The amount of minerals loss on the surface of the underlying rocks is determined by dependence:

$$P_2 = l \cdot 10^{-4}(10.2H)^{0.11d-42.84}\sqrt{0.02dHl^{1.184dH^{0.55}}} + m + \frac{9l}{(10.2H)^{0.1d}}, \qquad (12)$$

where P_2 – the productivity of the hydraulic elevator, m^3/t; m – a constant value characterizing the level of minimum consumption of minerals on the surface of the underlying rocks; for tuffs $m = 10\%$.

The results are presented in figure 4.

The working time of the excavation chamber is set as a fraction of the volume of the excavation chamber divided by the productivity of erosion of minerals (6) plus the volume of the underlying rocks that are being eroded by the depth of the timing of the useful component, divided by the productivity of erosion (10).

The working time of the excavation chamber is equal to the time of the roof collapse. If the working time of the camera exceeds the time of collapse, the correction of the camera span is made in the direction of its decrease, and the means of strengthening the security cells at depths

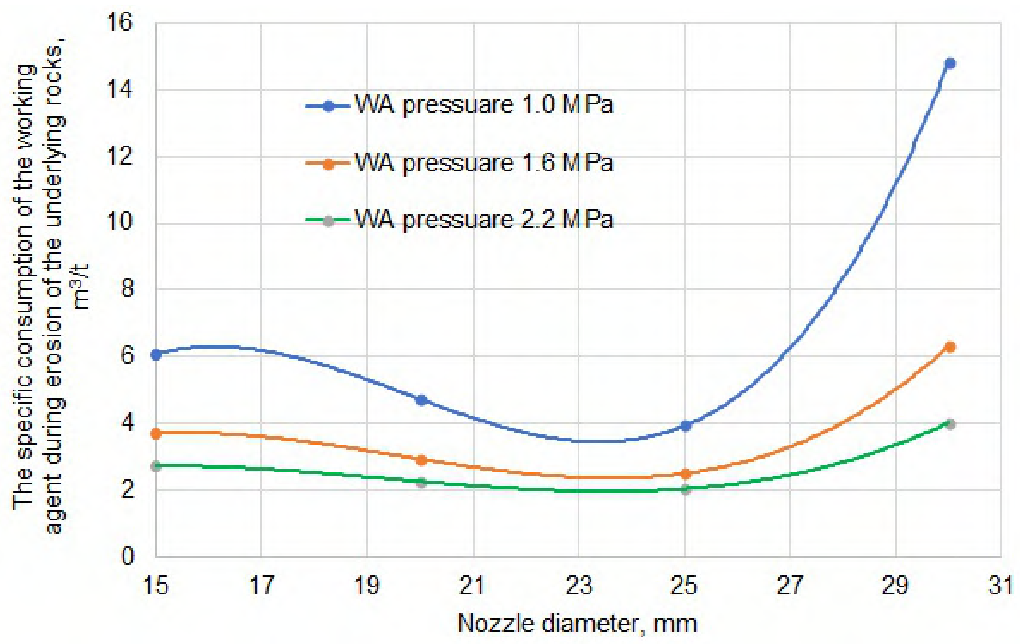

Figure 3. Dependencies of the specific consumption of WA when washing the underlying rocks on the diameter of the nozzle at variable pressure.

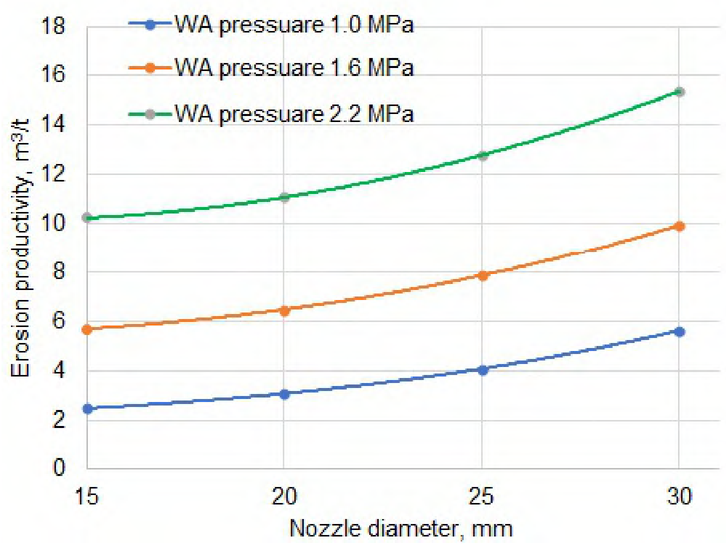

Figure 4. Dependence of hydraulic washing productivity on nozzle diameter at variable pressure.

of 50 m are provided by dividing the size of the reservoir capacity by the number of layers with the subsequent paving of the produced space.

The proposed technology of hydroerosion of tuffs and underlying rocks by the method of borehole hydro-mining has been experimentally investigated within the Rafaliv basalt deposit and is at the stage of implementation at PrJSC "Rafaliv Quarry" (Ivanchi village, Varas district, Rivne region, Ukraine).

3. Conclusions

Zeolite-smectite tuffs are increasingly used in the national economy, and due to their trace element composition, they are valuable raw materials for industry. Significant man-made reserves of tuffs in basalt quarries can be selectively extracted due to their weakening with water and subsequent screening, and with the well method of mining, weakening allows to increase the productivity of the process.

Based on the calculation of the hydroerosion process parameters of tuffs and underlying rocks, the shape of excavation chambers with the specified radius of erosion is recommended. The most rational forms of cameras, formed taking into account the radius and length of the span, are round, star-shaped and square.

The dependence of the productivity of tuff erosion in the chamber is presented, taking into account the working time, rock strength properties, chamber geometry, water consumption by the hydromonitor and air lift, and the energy consumption of the process. At the same time, the working time of the excavation chamber is adjusted with the time of the roof collapse and the strengthening of the security cells.

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References

[1] Peregudov V, Hryhoriev I, Joukov S and Hryhoriev Y 2020 *E3S Web of Conference* **166** 02004 URL https://doi.org/10.1051/e3sconf/202016602004
[2] Joukov S, Lutsenko S, Hryhoriev Y, Martyniuk M and Peregudov V 2020 *E3S Web of Conference* **166** 02005 URL https://doi.org/10.1051/e3sconf/202016602005
[3] Pysmennyi S, Fedko M, Shvaher N and Chukharev S 2020 *E3S Web of Conference* **201** 01022 URL https://doi.org/10.1051/e3sconf/202020101022
[4] Kyelgyenbai K, Pysmennyi S, Chukharev S, Purev B and Jambaa I 2021 *E3S Web of Conference* **280** 08001 URL https://doi.org/10.1051/e3sconf/202128008001
[5] Azarian V, Lutsenko S, Zhukov S, Skachkov A, Zaiarskyi R and Titov D 2020 *Mining of Mineral Deposits* **14**(1) 1–10 URL https://doi.org/10.33271/mining14.01.001
[6] Pysmennyi S, Fedko M, Chukharev S, Rysbekov K, Kyelgyenbai K and Anastasov D 2022 *IOP Conference Series: Earth and Environmental Science* **970**(1) 012040 URL https://doi.org/10.1088/1755-1315/970/1/012040
[7] Pysmennyi S, Chukharev S, Khavalbolot K, Bondar I and Ijilmaa J 2021 *E3S Web of Conference* **280** 08013 URL https://doi.org/10.1051/e3sconf/202128008013
[8] Lutsenko S, Hryhoriev Y, Peregudov V, Kuttybayev A and Shampykova A 2021 *E3S Web of Conference* **280** 01005 URL https://doi.org/10.1051/e3sconf/202128001005
[9] Blizniukov V and Lutsenko S 2017 *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu* **1** 44–49 URL http://nbuv.gov.ua/UJRN/Nvngu_2017_1_9

[10] Bolatova A, Kuttybayev A, Kainazarov A, Hryhoriev Y and Lutsenko S 2022 *News of the National academy of sciences of the Republic of Kazakhstan. Series of geology and technical sciences* **1(351)** 33–38 URL https://doi.org/10.32014/2022.2518-170X.137

[11] Lutsenko S 2017 *Quality – Access to Success* **18**(S1) 226–230 URL https://www.proquest.com/openview/87ac497268d7644e316b4c1bfc24d289/1?pq-origsite=gscholar&cbl=1046413

[12] Korniyenko V, Vasylchuk O, Zaiets V, Semeniuk V, Khrystyuk A and Malanchuk Y 2022 *IOP Conference Series: Earth and Environmental Science* **1049**(1) 012027 URL https://doi.org/10.1088/1755-1315/1049/1/012027

[13] Rakishev B, Orynbay A, Auezova A and Kuttybaev A 2019 *Mining Informational and Analytical Bulletin* **8** 83–94 URL https://doi.org/10.25018/0236-1493-2019-08-0-83-94

[14] Pysmennyi S, Chukharev S, Kyelgyenbai K, Mutambo V and Matsui A 2022 *IOP Conference Series: Earth and Environmental Science* **1049**(1) 012008 URL https://doi.org/10.1088/1755-1315/1049/1/012008

[15] Malanchuk Y, Korniienko V, Malanchuk L and Zaiets V 2020 *E3S Web of Conference* **201** 01036 URL https://doi.org/10.1051/e3sconf/202020101036

[16] Pysmennyi S, Peremetchyk A, Chukharev S, Fedorenko S, Anastasov D and Tomiczek K 2022 *IOP Conference Series: Earth and Environmental Science* **1049**(1) 012029 URL https://doi.org/10.1088/1755-1315/1049/1/012029

[17] Kovrov O, Babiy K, Rakishev B and Kuttybayev A 2016 *Mining of Mineral Deposits* **10**(2) 55–63 URL https://doi.org/10.15407/mining10.02.055

[18] Imashev A, Suimbayeva A, Zhunusbekova G, Zeitinova S, Kuttybayev A and Mussin A 2022 *Mining of Mineral Deposits* **16**(3) 61–66 URL https://doi.org/10.33271/mining16.03.061

[19] Kopesbayeva A, Auezova A, Adambaev M and Kuttybayev A 2015 Research and development of software and hardware modules for testing technologies of rock mass blasting preparation *New Developments in Mining Engineering* pp 185–192 URL https://doi.org/10.1201/b19901-34

[20] Adamaev M, Kuttybaev A and Auezova A 2015 Dynamics of dry grinding in two-compartment separator mills *New Developments in Mining Engineering* pp 435–439 URL https://doi.org/10.1201/b19901-76

[21] Rakishev B, Auezova A, Kuttybayev A and Kozhantov A 2014 *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu* **6** 22–27 URL http://www.nvngu.in.ua/index.php/en/component/jdownloads/finish/50-06/1521-2014-6-rakishev/0

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Justification of drilling parameters of a typical well in the conditions of the Samskoye field

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Justification of drilling parameters of a typical well in the conditions of the Samskoye field

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Abstract. In the Republic of Kazakhstan, there is a noticeable shortage of water resources, which is a consequence of the natural features of its territory and climate. In particular, there are big problems in the water supply to the Mangystau region. The main source of water in the region is the Samskoye groundwater field. In this work, the conditions of the Samskoye field are typified, the method and technological parameters for drilling a typical well are selected and substantiated. It has been established that rotary drilling with reverse circulation in the conditions of the Samskoye field has significant advantages. The maximum possible production rate of drilling with reverse circulation, taking into account the limited thickness of the aquifer, is 4.3 times higher than with rotary drilling with direct circulation and 2.5 times higher than with percussion drilling. With the same filter pipe diameter, the greatest possible thickness of the gravel pack layer in reverse circulation drilling is 15 times greater than for conventional rotary drilling and 3.7 times greater than for percussion drilling. Thus, the use of rotary drilling with reverse circulation will solve an important problem – the provision of domestic and drinking water supply to the area.

1. Introduction

Water resources play a crucial role in the economy of any country. An important resource is groundwater extracted from boreholes. The problem of the development and protection of groundwater of the Planet Earth is in the focus of attention of special UN organizations [1]. In the Republic of Kazakhstan, there is a noticeable shortage of water resources, which is a consequence of the natural features of its territory and climate. A significant part of its vast territory, including the center, south and west, belong to the zones of deserts and semi-deserts, characterized by rare precipitation and underdeveloped river networks. The earth's surface is often covered with salt marshes, and the permeable layers close to the surface contain waters with high mineralization and cannot be used for drinking purposes.

Since 2002, the country has been consistently implementing the programs "Drinking Water" for 2003-2010, "Ak-Bulak" for 2011-2020 and the State Program for the Development of Regions for 2020-2025.

The "Drinking Water" Program started in 2002. The goal of this program was the complete provision of drinking water to more than 7,000 settlements, including the installation of water

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supply systems in 174 villages and 86 towns. It lasted 8 years for its implementation, 195 billion tenge was allocated from the budget [2].

The second program, which was supposed to help provide Kazakhstan with clean drinking water, was launched in 2011 for a period of 9 years. The program was supposed to provide by 2020 with high-quality drinking water from centralized water supply systems the rural population of Kazakhstan by 85% and the urban population by 100%. For these purposes, it was planned to allocate a total of 1.3 trillion tenge. In 2011-2018, within the framework of the state program for the development of regions, 2015 projects were implemented from the republican budget for the development of water supply and sanitation systems [2].

Unfortunately, for a number of reasons, the implementation of these programs did not allow solving the problems of water supply in certain regions.

Mangystau is an industrial region. The basis of the economy is the oil and gas sector. In the structure of industry, the main share is occupied by the mining industry and quarrying, the share of which at the end of 2020 amounted to 85%. The industry employs about 25% of the population of the region, the share of the industry in the gross regional product is about 50%. Regional enterprises annually produce more than 10% of the industrial output of the country [3].

Based on the current demographic situation and the development of the region as a whole, the need for water supply in the region is growing every year. The water supply of the region is carried out from the Astrakhan-Mangystau water conduit and desalinated sea water, since there are few sources of natural groundwater. To date, drinking water consumption is 149 thousand m^3/day. There is a deficit in the region's water supply in the amount of 51 thousand m^3, and given the development of the region by 2025, the need will be 250-260 thousand m^3, and the deficit will be 100-110 thousand m^3 [4].

The implementation of the 2nd stage of bringing the capacity of the desalination plant "Kaspiy" to 40 thousand m^3/day has begun. JSC NC KazMunayGas is building a plant with a capacity of 17 thousand m^3/day at the Karazhanbas field.

To supply the city of Zhanaozen in the area of Kenderli and the village of Kuryk, it is planned to build desalination plants with a capacity of 50 thousand m^3/day, and on the territory of MAEC-Kazatomprom LLP with a capacity of 24 thousand m^3/day. It is planned to build a desalination plant with a capacity of 5 thousand m^3/day in the city of Fort Shevchenko [3].

Drinking water supply is provided by three sources and their share in the total volume of water consumption has the ratio:

- sea water – 52.4%;
- Volga water – 12.5%;
- groundwater – 35.1% [5].

2. Literature review

The Samskoye field is the main source of groundwater for the city of Zhanaozen. The field has been in operation since 1970. In 1979, the established total water withdrawal was only 0.02 thousand m^3/day, mainly due to private wells dug by the local population. Currently, the withdrawal of groundwater in the city of Zhanaozen has increased to 6.4 thousand m^3/day, which is 18% of the resources of the Samskoye field, although the problem of high-quality water supply to the city is still acute [6].

This problem can be solved only by significantly increasing the number of water wells and obtaining the maximum flow rate of groundwater of standard quality at the lowest cost.

Established according to the report [7] and approved for category B, the operational groundwater reserves are 21.2 thousand m^3/day for fresh water and 14.3 thousand m^3/day for slightly brackish water. The same values appear in modern documents [6].

For successful drilling of a well in the conditions of the Samskoye field, it is necessary to justify the drilling method, select drilling equipment, composition and parameters of the drilling fluid, rock cutting tools and drilling mode parameters.

As a rule, the main directions of scientific research are carried out in two main directions: solving issues related to the technology of cleaning a well from cuttings [8] and developing optimal parameters for the operation of a rock cutting tool [9].

Most often, drilling with direct circulation of drilling fluid is used for water wells. This technology is simple to organize, does not require additional equipment, and allows efficient use of the energy of the drilling fluid for the destruction of rocks [10].

However, with this circulation method, low drilling fluid flow rate, poor particle retention, low drilling efficiency, and severe wear of the drill bit are observed [11].

Another huge problem with this method is the high time and cost involved in combating fluid losses [12].

Usually, to eliminate this complication, the installation of casings or plugging of the absorbing layer in various ways is used [13]. However, when drilling wells for water, the use of these methods will only lead to unjustified expenditures of time and money.

The use of reverse circulation effectively solves the problem of drilling fluid losses in the well [14].

Reverse circulation drilling has proven to be highly effective in drilling wells for various purposes.

Thus, this method was successfully applied for the extraction of uranium ore by underground borehole leaching at operating technological wells of Volkovgeologiya, with an average total depth of 300-500 m [15].

There are examples of its use even in mine exploration instead of traditional core drilling, where reverse circulation drilling has high drilling efficiency and low cost [16].

According to [17], compared with traditional core drilling, drilling with reverse air circulation increased drilling efficiency by 70-90% while reducing costs by 30–50%, the number of accidents during drilling decreased by 60-70%.

It should be noted that the reduction of accidents is the most important factor in improving the efficiency of drilling wells, since the cost of repairs significantly increases the cost of well construction [18].

Airlift reverse circulation drilling showed high efficiency when drilling geothermal wells [19].

The application of airlift reverse circulation drilling technology is possible even in the construction of well with a depth of 4200 m, which is the deepest geothermal well in China [14].

Note that another possible application of reverse circulation with the help of an airlift is not drilling a well, but expanding it with the help of jet jets [20].

The experience of using this technology in drilling wells for gas hydrates is also known [21].

Thus, in recent years there has been a steady trend towards expanding the scope of drilling wells with reverse circulation of drilling fluid. This is due to the fact that this method has a number of significant advantages.

Thus, the use of reverse circulation drilling allows drilling wells with a diameter of up to 1500 mm [22].

Reverse circulation drilling technology is much more efficient, has better technical support and will play an increasingly important role in water well drilling in the future [23].

When using this method, the well production rate increases by about 30% compared to direct circulation drilling [24].

The key parameters of the drilling technology with reverse circulation and airlift gas injection are the volume of gas injection and displacement of the drilling fluid, the change of which regulates the bottomhole pressure [25].

It should be noted that reasonable recommendations do not include a choice of parameters for reverse circulation mechanisms and a large number of design flaws hinder the wide practical application of this drilling method [26].

Thus, the **purpose of the article** is to typify the conditions of the Samskoye field, choose the drilling method and justify the technological parameters of drilling a typical well, which will solve an important problem – providing household and drinking water supply to this area.

3. Results

On the territory of the Mangystau peninsula, surface water is practically absent. Since the sixties, exploration work has been carried out here, which made it possible to discover a number of groundwater deposits suitable for development.

A typical field is the Samskoye field. In the course of exploration work for 1968-1969, according to the report [7], this field has the following features. It has a total area of 1500 km^2 and is composed of Quaternary field of the North Ustyurt trough. Water-bearing formations have the form of lenses of various shapes and sizes. They are represented by fine-grained sands with small admixtures of medium and fine-grained sands.

The field has been in operation since 1970. A number of wells have been drilled, mainly by hand, as well as by UGB-50 drilling rigs. These wells are characterized by a low flow rate; their depth does not exceed 50 m, and their diameter is 150 mm.

According to the degree of water mineralization, the deposits are divided into two groups. The first group includes fresh waters with salinity up to 1 g/l (in fact, mineralization from 0.2 to 1 g/l occurs). These waters belong to the hydrocarbonate-chloride-sodium type. The second group includes slightly brackish waters with salinity up to 3 g/l. Waters of the first type are suitable for drinking needs of the population, waters of the second type can be used for technical needs and for the needs of cattle breeding.

Water-bearing rocks are mainly represented by fine-grained sands with small admixtures of medium– and fine-grained sands. Aquifers are generally highly homogeneous. The values of the filtration coefficient in general are in the range from 1 to 12 m/day, but in most cases they do not go beyond the range of 5.6-7.0 m/day. Waters are characterized by low pressure.

Roof and bottom rocks for aquifers are usually loams, less often they are represented by sandy loams, sandstones on lime cement and clays.

The depth of occurrence of fresh waters established by the mentioned studies is in the range from 1.5 to 44 m, the thickness of aquifers, according to modern data, reaches 39 m with an average value of 14 m. Aquifers of weakly brackish waters are located below the aquifers of fresh waters and are separated from them by layers of aquicludes.

In the article [27] based on the study of the geological and technical conditions of the Samskoye field, it was substantiated that the use of a rotary drilling method with reverse circulation makes it possible to multiply the well flow rate; reduce their required number; improve the quality of produced water; drastically reduce the well completion time; significantly lengthen the time of operation of wells; provide high rate of penetration (ROP); reduce the cost per cubic meter of produced water. Below, in support of this proposal, mathematical algorithms are given that allow obtaining the necessary numerical characteristics.

In order for the mathematical apparatus to be focused on the specific geological and hydrogeological conditions of the considered groundwater deposit, a basic model of a water well was built, which must meet the requirements of the following factors.

Economic factors:

- the maximum possible production rate of water;
- the maximum degree of its purification from mechanical impurities;
- minimum costs for the equipment of the water intake and for experimental pumping;

- minimum costs for current and workover of the well;
- maximum ROP;
- minimal time spent on round trips and drill string extensions;
- minimum cost of the drill string;
- the possibility of exploration and development of productive layers located below those that are known at the moment.

Geological and hydrogeological factors:

- depth of the productive aquifer;
- productive formation capacity;
- its mineralogical composition;
- filtration coefficient;
- reservoir pressure;
- types of rocks included in the well section;
- drillability of rocks.

Technological factors:

- ensuring the speed of the upward fluid flow, which guarantees the cleaning of the bottomhole from cuttings and a high ROP;
- using an airlift method to create a reverse circulation;
- ensuring the efficient operation of the airlift at the greatest planned depth of the well;
- taking into account the fact that the maximum height of the updraft corresponds to the upper position of the swivel on the mast.

Taking into account the above requirements, the following typical model for drilling a water well was adopted

The depth of a typical well is assumed to be 200 m.

This is justified by the following arguments:

- Established by earlier studies, the depth of fresh water (with salinity below 1 g/l) at the Samskoye field reaches 44 m, and the thickness of aquifer lenses reaches 39 m. Summing up these two figures, we obtain the depth of the base of the aquifer 83 m. The fact that the aquifers are composed, as a rule, of fine-grained sands, we take the length of the settling tank to be 15 m. Thus, the maximum depth of a well drilling into fresh water that exists at the moment can be 98 m;
- In addition to fresh water, it is also planned to use waters with a higher (up to 5 g/l) salinity. Such waters are used for technical and agricultural needs. According to the exploration work carried out, the brackish water aquifers are located below the fresh water aquifers and are separated from them by layers of aquicludes. Thus, the maximum required depth may be significantly greater;
- The given parameters of water wells refer to exploration work carried out before 2012 [6]. The possibility of discovering exploitable aquifers when drilling wells to great depths should hardly be ruled out;
- The study of the features of drilling water wells by the proposed method to a depth of 200 m (and possibly even more) will allow a more complete assessment of the proposed method of drilling.

The depth of the roof of the productive aquifer is assumed to be 170 m.

Based on the previous paragraph, in which, according to the considerations given there, it was decided to take the depth of a typical well equal to 200 m, the location of the aquifer was accordingly shifted down.

The aquifer has a thickness of 14 m.

According to available materials, this is the average thickness of productive aquifers containing fresh water.

The filtration coefficient of permeable rocks of the aquifer is 6.3 m/day.

The aquifers of the Samskoe field are composed of homogeneous fine-grained sands and are characterized by the indicated average value of the filtration coefficient.

The static head of a productive formation penetrated by a typical well is assumed to be 100 m.

This is justified as follows:

- the available materials do not allow to establish the average value of the static head for the drilled wells of the Samskoye field;
- since the depth of a typical well is assumed to be 200 m, which is at least 100 m higher than the depth of water wells drilled to date, then, accordingly, the water in this well may have a static head of the order of 100 m.

The diameter of a typical well is assumed to be 800 mm.

This is justified as follows:

- according to the literature data [28], the diameters of water wells drilled by the rotary method with reverse circulation can be in the range from 300 to 1500 mm;
- most often such wells have a diameter of 500 or 800 mm;
- with an increase in the diameter, the possible flow rate of the well increases;
- the required length of the receiving part of the well is reduced;
- the quality of mechanical water purification is improved due to the creation of a powerful layer of gravel;
- simplifies the technology of creating gravel;
- the required time of experimental pumping is reduced;
- at the same time, with an increase in the diameter of the well and, accordingly, the volume of the destroyed rock, the required amount of circulating drilling fluid increases;
- when passing through permeable layers, there is a high degree of absorption of drilling fluid in the walls of the well, which requires the continuous supply of new volumes of water;
- the ROP decreases;
- taking into account the above, and also, taking into account the low filtration coefficient, in the water-bearing rocks of the Samskoye field, which causes a relatively small loss of circulation, the largest of the two most commonly used diameters is 800 mm.

A drill string is accepted from commercially available pipes with a diameter of 146 mm (inner diameter 136 mm).

This is justified as follows:

- according to literature data [28] for rotary drilling with reverse circulation, drill pipes with a diameter of 127, 146, 168 and 219 mm can be used;
- with an increase in the bore section of drill pipes, the hydraulic resistance to the upward flow decreases sharply;
- the content of sludge in it decreases;

- at the same time, the required water supply is increased;
- sharply increase the time spent on round trips and build-up;
- commercially available pipes cannot be used in airlift drilling without significant modification, and their threaded connections are replaced with flanged ones, which drastically slows down the process of connecting pipes into a string and increases the total cost of work;
- the minimum diameter of the drill string, when implementing the proposed new solution, is 146 mm.

The height of the sludge-containing water-air mixture above the earth's surface is assumed to be 10 m.

This is justified as follows:

- the maximum lifting height of the cuttings-containing mixture corresponds to the height of the swivel at the moment of resumption of drilling after the drill string is built up;
- this height is equal to the height of the mast of the drilling rig, minus the dimensions of the blocks, hook, shackle, etc., as well as the distance that ensures the necessary maneuver (for example, raising the drill string above the clamp holding it before lowering it into the well);
- height of masts of rigs intended for rotary drilling with reverse circulation varies from 8.2 to 18.5 m [29] and averages 13 m; from installations of a similar purpose, the UGB3UK-OP installation has a mast height close to the indicated average value (14.2 m);
- thus, minus the average height of the mast 3-4 m, we get the average height of the swivel in its uppermost position, equal to 10 m.

The speed of the upward flow of water is 2.5 m/s.

This is justified as follows:

- the main advantage of rotary drilling with reverse circulation is the high speed of the upward flow, which ensures effective cleaning of the bottomhole from destruction products;
- this advantage is achieved due to a multiple decrease in the cross-sectional area of the channel through which the ascending flow moves;
- if during direct circulation speed of the upward flow rarely reaches 1 m/s, then according to the literature [28] during reverse circulation, it should be in the range from 1.5 to 3.5 m/s;
- at upstream speeds that do not reach the lower limit of this interval, the advantages of drilling with reverse circulation are lost, and in order to reduce the amount of cuttings formed per unit time, it is necessary to resort to reducing the diameter of the wellbore to normal sizes;
- when the upper limit of the specified interval is reached, the removal of large particles is ensured, the size of which is close to the inner diameter of the drill pipes and the discharge hose;
- aquifers of the Samskoe field are homogeneous in their mineralogical composition and, as a rule, are composed of fine-grained sands [7]; there is no information on the presence of large pebbles and, especially, boulders;
- for the indicated reasons, when drilling a typical well, the upward flow rate will be maintained at the level of the average value over the given interval – i.e. 2.5 m/s [30].

The value of the average ROP in the enclosing rocks is assumed to be 15 m/h.

This is justified as follows:

- when drilling in aquifers composed of fine-grained sands, the penetration rate may exceed 100 m/h;

- the limiting factor is the supersaturation of the upward flow with sludge and an unacceptable increase in its total density;
- a sharp increase in the density of the upward flow can negate the effect of aeration – the speed of the upward flow will drop to zero and the bit will be stuck with cuttings;
- in connection with the indicated risks, the ROP during the passage of the aquifer should be restrained to values that are typical for the host rocks;
- the rocks hosting the aquifers in the field under consideration are clays and loams, therefore the accepted ROP of 15 m/h is quite progressive for these rocks when drilling with reverse circulation and, at the same time, quite achievable;
- the calculations below will show that at this ROP there will be no unacceptable increase in the density of the updraft.

The depth of the mixer is assumed to be 2 m less than the depth of the well. This is justified as follows:

- fluid circulation in the airlift method is carried out due to the fact that at the mixer level a difference in hydrostatic pressures is created in the annulus filled with water and in the drill string filled with water-air mixture;
- at an extremely low (which corresponds to the stated ratio) location of the mixer, the maximum height of the mixture column is achieved, and hence the maximum value of the difference mentioned above;
- due to this difference, the maximum speed of the upward flow is created and, accordingly, the best cleaning of the bottomhole from cuttings;
- starting from a certain drilling depth, due to the limited pressure of the compressor, the resumption of airlift circulation after technologically necessary stops (for example, when building up the drill string) becomes impossible;
- to resume circulation, the immersion depth of the mixer has to be reduced;
- at the same time, the height of the mixture column and the difference in hydrostatic pressures inside and outside the drill string decrease with a corresponding decrease in the circulation intensity;
- the existing methods of separating the operating conditions of the compressor during the resumption of circulation and during the normal drilling process are reduced to significant complications in the design of the drill string.

Summarizing, we will present the main parameters of drilling a typical well in a summary (table 1).

Below are calculations of possible results of the practical application of the above typical model of rotary drilling with reverse circulation.

The well flow rate is determined by the possibility of creating the necessary drawdown on the productive formation. During pumping, this drawdown (i.e. pressure reduction) is created by lowering the water level in the pay zone near the wellbore. This reduction is:

$$S = h_D - h_S \tag{1}$$

where h_D is the dynamic level (i.e. the distance from the surface to the water in the well during pumping), h_S is the static level (the same level before pumping). The static level is also defined as:

$$h_S = h_p - H_S \tag{2}$$

where h_P is the formation top depth, H_S is the static head.

Table 1. Basic drilling parameters of a typical well.

No.	Parameter name	Meaning
1	Drilling depth, N, m	200
2	Depth of the roof of the productive formation, N_R, m	170
3	Reservoir thickness, m	14
4	Filtration coefficient, K_F, m/day	6.3
5	Static formation head, H_S, m	100
6	Drilling diameter, D, mm	800
7	Drill string diameters: out./in., d_O/d_i, mm	146/136
8	The height of the mixture above the surface, h, m	10
9	Upward water flow rate, U_W, m/s	2.5
10	Rate of penetration, ROP, m/h	15
11	Mixer immersion depth, L, m	2H

During pumping, the flow rate corresponding to the decrease (in m^3/h) is determined by the formula [31]:

$$Q_S = \frac{SK_F m}{36} \tag{3}$$

where m is the thickness of the aquifer in m; K_F is the filtration coefficient in m/day.

In confined aquifers, according to formula (2), the largest possible decrease is a decrease by the value of the static head.

$$S_{max} = h_P - h_S \tag{4}$$

In unconfined aquifers, this formula is reduced to:

$$S_{max} = h_F - h_S \tag{5}$$

where h_F is the depth of the base of the productive formation.

When trying to achieve the maximum flow rate from this particular well, an important limitation is to prevent catastrophic production of reservoir material from the walls of the well, caused by an excessively high rate of water withdrawal.

The criterion here is the maximum allowable rate of water filtration through the formation pores in the receiving part of the well. The maximum filtration rate (in m/h) is determined by the formula:

$$U_F = 2.71\sqrt[3]{K_F} \tag{6}$$

where K_F is the filtration coefficient in m/day.

From formula (6) it can be seen that the maximum allowable velocity drops sharply (in cubic dependence) with a decrease in the filtration capacity of the productive formation.

Taking into account the above limitation when pumping water from a given well, the maximum allowable flow rate in m^3/h is determined by the formula:

$$Q_{max} = FU_F \tag{7}$$

where F is the surface area of the well in m^2 through which water enters (corresponding to the area of the filter).

Subject to the condition of not exceeding the allowable filtration rate, the highest allowable well flow rate is achieved by varying the filter parameters.

Given the cylindrical shape of the well, formula (7) can be written as

$$Q_{max} = L\pi DU_F \tag{8}$$

where L is the length of the receiving part in m; D is the diameter of the receiving part in m.

Formula (8) shows that the surface F can be reached in three ways (or using their combination):

(i) By increasing the length of the filter – the most practical and least expensive way. The required length of the receiving part is equal to:

$$L_{max} = \frac{Q_{max}}{\pi DU_F} \tag{9}$$

However, the application of this method is limited by the thickness of the productive formation m. Taking into account the capacity, the maximum possible well flow rate is determined as follows:

$$Q_{max} = m\pi DU_F \tag{10}$$

(ii) By increasing the diameter of the receiving part, which is usually associated with complex additional operations to expand it:

$$D_{max} = \frac{Q_{max}}{\pi LU_F} \tag{11}$$

(iii) By drilling a well with a large diameter, which is ensured by the use of rotary drilling with reverse circulation.

We use the results of the methodology presented in formulas (1)-(11) to evaluate the effectiveness of the method of rotary drilling of wells with reverse circulation in comparison with two other drilling methods used in drilling water wells – a rotary method with direct circulation and a shock-rope method.

In a comparative assessment of drilling methods, the main role is played by the maximum possible diameters of the bits when using them (without taking into account the possibility of expanding the receiving part).

For rotary drilling with reverse circulation we accept the diameter value equal to 800 mm (table 1).

For rotary drilling with direct circulation in the case of using the widespread installation 1BA-15V, the final diameter (i.e., the one with which the productive aquifer is opened) can be a diameter of 190 mm [32].

When percussion drilling with a rig UKS-22 the size of the first casing cannot exceed 600 mm (i.e. 22 inches in inner diameter). When designing a casing telescope specific to percussion drilling, each subsequent casing must be at least 2 inches smaller than the previous one, with the protrusion of one casing from under the other increasing with decreasing diameter.

From table 2 it follows that when building a well with a depth of 200 m and a diameter of the first casing of 22 inches, the required depth can be achieved, taking into account the above conditions, by creating a telescope of 6 casings. In this case, the diameter of the receiving part of the well is equal to the outer diameter of the last (sixth) casing – i.e. columns with an outer diameter of 12 inches (324 mm).

The initial data given in lines 1-5 of table 1 were taken as the basis for comparative calculations.

Given in table 3 the maximum theoretical (excluding restrictions) flow rate of each of the 3 wells is determined by formula (3). The maximum possible value, namely the static head H_S, is taken as the reduction in S.

According to formula (6), the admissible filtration rate $U_F = 5.01$ m/h was obtained.

The results of comparative calculations are given in table 4.

Table 2. Typical design of a percussion-rope drilling well with a depth of 200 m.

Column number in descending order	1	2	3	4	5	6
Column diameter, inches	22	20	18	16	14	12
Exit (length of contact with rock), m	10	20	30	40	50	50

Table 3. General parameters used in the comparative analysis of three drilling methods.

No.	Parameter name	Meaning
1	Maximum possible theoretical flow rate, Q_S, m^3/h	245
2	Depression required to achieve it, H_S, m	100
3	Permissible filtration rate, U_F, m/h	5.01

Table 4. Main indicators of drilling water wells.

Parameter name	Rotary drilling	Percussion drilling	Reverse circulation drilling
Diameter of the receiving part D, m	0.190	0.324	0.800
Filter pipe diameter D_F, m	0.146	0.146	0.146
Sprinkling layer thickness δ, m	0.022	0.089	0.327
Required filter length at a flow rate of 245 m^3/h (table 3), L, m	82	48	20
The highest production rate (at reservoir thickness $m = 14$ m), Q_{max}, m^3/h	41	71	176

4. Conclusions

According to the results of the work, rotary drilling with reverse circulation in the conditions of the Samskoye field has such advantages.

The maximum possible production rate of drilling with reverse circulation, taking into account the limited thickness of the aquifer, is 4.3 times higher than with rotary drilling with direct circulation and 2.5 times higher than with percussion drilling. These results are ratios of accepted diameters. For this reason, the maximum achievable, according to formula (10), flow rate may increase or decrease depending on the thickness of the reservoir m, but the indicated ratio of maximum flow rates will remain the same.

If the reservoir thickness is not a limiting factor, then with the same flow rate (formula (3)), the indicated ratio will be valid for the required lengths of the receiving part calculated by formula (9). The larger the diameter, the smaller the required length (line 4 of the table), with a decrease in which the costs of both the equipment of the receiving part and its repair are reduced.

With the same diameter of the filter pipe (line 2 of the table), the maximum possible thickness of the gravel pack layer during reverse circulation drilling is 15 times greater than for conventional rotary drilling and 3.7 times greater than for cable percussion drilling.

Powerful gravel sprinkling provides the best quality of mechanical cleaning of the sampled water. The consequence of this is also the minimum time required for experimental pumping and the minimum length of the well sump. Such sprinkling also provides the maximum duration of overhaul operation.

It should be noted that with rotary drilling of large diameter wells with reverse circulation, labor costs for the manufacture of a gravel pack are minimized. As a rule, gravel is filled manually through the wellhead, since the large area of the annular space eliminates the possibility of plugging and failure of the filled material to reach the receiving part.

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References

[1] Kozlovsky E A (ed) 1988 *Hydrogeological Principles and Groundwater Protection* vol 1: Handbook of scientific methods (Moscow: UNESCO/UNEP) URL https://unesdoc.unesco.org/ark:/48223/pf0000099378
[2] Torebaeva M 2021 Why Kazakhstan may be left without drinking water by 2050 URL https://cronos.asia/ekologiya/pochemu-k-2050-godu-kazahstan-mozhet-ostatsya-bez-pitevoj-vody
[3] Government of the Republic of Kazakhstan 2021 On the approval of the Comprehensive Plan for the Socio-Economic Development of the Mangystau Region for 2021-2025 and the invalidation of some decisions of the Government of the Republic of Kazakhstan URL https://adilet.zan.kz/rus/docs/P2100000784
[4] Government of the Republic of Kazakhstan 2014 On approval of the 'Ak Bulak' Program for 2011-2020 URL https://adilet.zan.kz/rus/docs/P1100000570
[5] 2003 On the Regional Program of the Mangistau region 'Drinking Water' for 2003-2010 URL https://adilet.zan.kz/rus/docs/V03M0001438
[6] Committee for Water Resources of the Ministry of Agriculture of the Republic of Kazakhstan 2012 The concept of water supply in the Mangistau region
[7] Sydykov Z S, Kukabaev B I, Kugeshev A K, Vishnyakov A S and Kulikov G V 1970 *Underground waters of the Mangyshlak-Ustyurt oil and gas province* (Academy of Sciences of the Kazakh SSR, Institute of Hydrogeology and Hydrophysics)
[8] Ighnatov A 2016 *Mining of Mineral Deposits* **10**(2) 85–90 URL https://doi.org/10.15407/mining10.02.085
[9] Ratov B T, Fedorov B V, Khomenko V L, Baiboz A R and Korgasbekov D R 2020 *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu* **2020**(3) 13–18 URL https://doi.org/10.33271/nvngu/2020-3/013
[10] Ihnatov A 2021 *Mining of Mineral Deposits* **15**(3) 122–129 URL https://doi.org/10.33271/mining15.03.122
[11] Cheng L, Man G X, Zhu L Q, Wang H L, Ren L K and Wang K 2014 *Drilling Engineering* **3** 44–47 URL https://doi.org/10.3969/j.issn.1672-7428.2014.03.015
[12] Sudakov A, Chudyk I, Sudakova D and Dziubyk L 2019 *E3S Web of Conferences* **123** 01033 URL https://doi.org/10.1051/e3sconf/201912301033
[13] Chudyk I I, Femiak Y M, Orynchak M I, Sudakov A K and Riznychuk A I 2021 *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu* (4) 17–22 URL https://doi.org/10.33271/nvngu/2021-4/017
[14] Yong Z and Jianliang Z 2014 *Procedia Engineering* **73** 243–251 URL https://doi.org/10.1016/j.proeng.2014.06.194
[15] Karmanov T D, Kaliyev B Z and Assanov N S 2021 *IOP Conference Series: Materials Science and Engineering* **1047**(1) 012163 URL https://doi.org/10.1088/1757-899X/1047/1/012163
[16] Yuan Z, Geng J and Xiong L 2014 *Coal Geology of China* **26**(1) 63–66 URL https://doi.org/10.3969/j.issn.1674-1803.2014.01.13

[17] Su J 2021 *Drilling Engineering* **48**(12) 38–42 URL http://en.cgsjournals.com/article/doi/10.12143/j.ztgc.2021.12.007
[18] Ihnatov A O, Haddad J, Stavychnyi Y M and Plytus M M 2023 *Journal of The Institution of Engineers (India): Series D* **104** 119–130 ISSN 2250-2130 URL https://doi.org/10.1007/s40033-022-00402-5
[19] Yang Z Y, Jia Z, An Z Y and Huang X L 2018 *Drilling Engineering* (1) 34–38 URL https://doi.org/10.3969/j.issn.1672-7428.2018.01.009
[20] van der Schans M L, Bloemendal M, Robat N, Oosterhof A, Stuyfzand P J and Hartog N 2022 *Groundwater* **60**(6) 808–819 URL https://doi.org/10.1111/gwat.13203
[21] Kozhevnykov A, Khomenko V, Liu B C, Kamyshatskyi O and Pashchenko O 2020 *Key Engineering Materials* **844** 49–64 URL https://doi.org/10.4028/www.scientific.net/KEM.844.49
[22] Kenzhetaev Z S, Kuandykov T A, Togizov K S, Abdraimova M R and Nurbekova M A 2022 *News of the National Academy of Sciences of the Republic of Kazakhstan* **3**(453) 115–127 URL https://doi.org/10.32014/2022.2518-170X.184
[23] Wang Y 2016 *Shandong Coal Science and Technology* (7) 158–160 URL https://doi.org/10.3969/j.issn.1005-2801.2016.07.069
[24] Xiumin M, Yue C and Luheng Q 2014 *Procedia Engineering* **73** 252–257 ISSN 1877-7058 2014 International (China) Geological Engineering Drilling Technology Conference (IGEDTC2014) URL https://doi.org/10.1016/j.proeng.2014.06.195
[25] Li Q, Zhang X, Li Z, Li J and Dai F 2021 *Journal of Southwest Petroleum University (Science & Technology Edition)* **43**(4) 35 URL https://doi.org/10.11885/j.issn.16745086.2021.04.29.01
[26] Okere C J, Su G, Zhou J, Li G and Tan C 2021 *IOP Conference Series: Earth and Environmental Science* **814**(1) 012005 URL https://doi.org/10.1088/1755-1315/814/1/012005
[27] Biletskiy M T, Ratov B T, Khomenko V L, Borash B R and Borash A R 2022 *News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences* **2022**(5) 51–62 URL https://doi.org/10.32014/2518-170X_2022_5_455_51-62
[28] Dudlia M, Pinka J, Dudlia K, Rastsvietaiev V and Sidorova M 2018 *Solid State Phenomena* **277** 44–53 URL https://doi.org/10.4028/www.scientific.net/SSP.277.44
[29] Ihnatov A, Koroviaka Y, Rastsvietaiev V and Tokar L 2021 *E3S Web of Conferences* **230** 01016 URL https://doi.org/10.1051/e3sconf/202123001016
[30] Ihnatov A O, Koroviaka Y A, Pinka J, Rastsvietaiev V O and Dmytruk O O 2021 *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu* (1) 11–18 URL https://doi.org/10.33271/nvngu/2021-1/011
[31] Dudlya M, Sirik V, Rastsvetaev V and Morozova T 2014 Rotary drilling system efficiency reserve *Progressive Technologies of Coal, Coalbed Methane, and Ores Mining* ed Bondarenko V, Kovalevs'ka I and Ganushevych K (London: CRC Press) pp 123–130
[32] Ihnatov A O, Koroviaka Y A, Haddad J, Tershak B A, Kaliuzhna T M and Yavorska V V 2022 *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu* (1) 20–27 URL https://doi.org/10.33271/nvngu/2022-1/020

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Determining key features of the operation of percussion downhole drilling machines

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Determining key features of the operation of percussion downhole drilling machines

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Abstract. Dnipro University of Technology is a leading institution where an authoritative scientific school was formed to solve the fundamental issues of percussive-rotary drilling with the help of hydraulic hammers. This method makes it possible to intensify significantly the mining processes of rock mass breaking. In order to perform the specified function as fully as possible, hydraulic hammers are to work in a certain technological mode and have appropriate technical characteristics; the paper deals immediately with the analysis of those characteristics. The original designs of hydraulic hammers proposed by the authors are distinguished by a high degree of reliability of the interaction of individual parts and assemblies. Simulation of the operation of hydraulic hammers under appropriate mode-parametric support revealed a number of their significant advantages, i.e. in terms of creating effective conditions for rock mass disintegration. It has been proven convincingly that some features of the approaches to the implementation of a hydraulic well washing programme correspond to the stability of a high-quality process of the downhole work of percussion machines. As a result of the research, a composition of some rational formulations of flushing fluids, which contribute to a significant acceleration of the development of destructive processes, was clarified.

1. Introduction

Further sustainable innovative development of mining and other related industries is impossible without wide application of drilling well technologies. And for the latter, in the near future, there are no real technically and technologically justified alternatives [1].

In the generalized sense of this well-established and widely used terminological expression, drilling different-purpose wells helps solve a significant range of production and theoretical issues related to the need to search for promising structures for the available useful components and study the specific geological and technical conditions of stratified mineral deposits with further creation of powerful industrial complexes for their effective extraction and partial local processing [2].

Modern engineering and technologies of well construction face rather complex but extremely necessary tasks of obtaining comprehensive multifaceted information, which source, first of all, is represented by core samples of rock formations [3]. In relation to wells of the large number of operational wells, the main requirement is the formation of a communication channel suitable for long-term operation with a mineral deposit in the rock layer. Taking into account the above, the following can be stated confidently: completeness and perfection of the geological and industrial task of deposit development depends on the quality of operations related to well construction in the rock mass; moreover, the latter should contain comprehensive and concrete details.

The multi-factorial cycle of well construction with its indispensable component in the form of various bottomhole drilling processes (in other words, phenomena of rock mass breaking), will be effective only while observing a certain mode of interaction of a drilling rock-breaking tool with the rock mass. Thus, in terms of well layout, the connection links of a rock-breaking tool with the surface energy and power equipment, there is a significant number of functional elements designed to rationalize maximally each factor of the complex operation of rock bottomhole disintegration. The above should be supplemented by the fact that well technologies allow carrying out effectively a cycle of operations to solve complicated issues, e.g. preparation of territories for future construction of civil and industrial complexes as well as necessary technological support for proper execution of the specified operations [4].

Summing up, it is possible and necessary to highlight significant complexity of the structural design of drilling processes, which features are determined by the ultimate goal of well construction. Due to the fact that well drilling can have different purposes, the specified rock formations have a significant range of options for their dimensional design and spatial position in the rock mass. The well depths determined by the stratigraphic location of a specific mineral deposit or by special instructional requirements for the technology of drilling and testing differ greatly in their absolute values. As for the wellbore diametrical characteristics, their values are specified, in particular, by the requirements for the representative qualities of rock samples as well as the overall dimensions of the research and operational equipment of wells.

In such a formulation of the analysis of problematics of drilling operations, one can trace a clear need to apply the substantiated (from the standpoint of minimized capital costs) approaches to the development of regulations for their construction; that will also contribute to the complete avoidance of complications and accidents in shafts of the considered specific mining operations.

2. Related work

According to the conducted analysis of literature sources and information reports of production organizations engaged in drilling and related operations, it is possible to talk about current and prevailing trend – improvement of rock-destroying tools to increase their operating resource on the well bottom [5]. The following remark will be relevant here: a new rock-breaking tool is intended mostly for its use in terms of classic rotary drilling. The given data can be also explained by the fact that almost all technical means of drilling operations are designed and adapted to carry out corresponding operations using rotation (rotary, in case of oil-and-gas well construction) method of rock mass breaking. The latter is the most widely used one; though, it has significant defects, which essence is exclusively in those factors being the basis of functional principles of the method under consideration [1].

Generally, mechanical methods of rock mass breaking are distinguished by a too low coefficient of efficiency due to the fact that they are characterized by unjustified energy dissipation in most technological schemes of their implementation. That refers to large power losses due to drill string friction against the well walls during its necessary rotation as well as bottomhole interaction of a rock-breaking tool with the rock mass with further heat release. The described phenomena are objective and the ones that cannot be eliminated without fundamental transformations of a technological scheme of the rotary drilling method [4]. In fact, such a state of affairs has resulted in the development of a number of effective and promising non-mechanical methods that apply useful phenomena of physical or chemical origin to form breaking forces within the drilling tool-rock contact zone of a special design.

Modelling, extensive testing, and, in some cases, even industrial implementation of multifaceted forms of non-mechanical methods have proven their important potential advantages and wide opportunities. However, their relatively large-scale application in the practice of well construction is hindered by the need to make changes, sometimes quite significant, in the construction schemes of the corresponding technological cycles. It will be appropriate here to provide examples of partial application of some principles of non-mechanical methods of forming wells in rock mass. In particular, that refers to high-pressure jets of washing fluid, which hydraulic organs are woven organically into the drill bit structure [6]. In the context of such a technical solution, it is possible to intensify significantly a course of destructive processes and their further development in terms of effective drilling mud removal from the well bottom [7]. Additional introduction of interaction of high-pressure jets with a rock mass of various-origin abrasive materials into a circulation chain can bring significant positive changes at almost all stages of the formation of a rock mass breaking zone [8].

While applying this method, it is possible to observe an extremely intensive development of complex deformation and subsequent breaking phenomena in the rock mass; ultimately, that allows obtaining high indicators of the wellbore deepening. It can be explained by the significance of dynamic level of application of breaking forces to the rock, which cannot be achieved by other methods and techniques. The conducted studies proved the expediency of such an interpretation of effective rock-breaking methods, when the variants of conditional periodicity of applying the required values of axial load occurs due to the presence of not only abrasive-jet percussion effects but also the generation of directed shock pulses by special impact machines. A convincing advantage of the described modifications of the well formation methods is the possibility of controlled adjustment of the frequency characteristics to a higher degree of a dynamic process of the breaking element-rock interaction. It is implemented by complementing the design with special downhole machines and a corresponding complex tool of certain design of components, developed to act as a so-called downhole regulator as comprehensively as possible. They should function to coordinate the requirements of a well construction technology regarding the proposed combined drilling methods and capabilities of the drilling mechanisms. Percussion downhole machines are to form appropriate pulses of a clearly defined amplitude with the possibility of direct and operational adjustment from the surface; according to the general definition of this concept, a drilling tool should be able to relay and transform shock pulses to the rock bottomhole of the well as fully as possible [9].

The design and implementation of special measures of a hydraulic well flushing programme with the mandatory use of appropriately activated technological indicators of circulating drilling fluids is the additional and very influential factor for a proper downhole breaking process [10].

The represented reasoned data indicates indisputably the available urgent needs for further comprehensive development and industrial implementation of sufficiently effective technical means and technologies for well construction with the adequate multi-category indicators.

3. Results

A complex cycle of well drilling consists of several sequentially performed operations; rock breaking is the most responsible one from the viewpoint of reaching high production and economic indices [11]. A rock breaking method determines almost all technical and technological features of well drilling regulations. It is the method that influences directly the course of downhole breaking processes, which, under conditions of well construction in the rocks prone to manifestation of various complications, must be planned in a logical sequence to prevent violation of the execution completeness of all necessary well technological operations [12].

Overall, a drill well is a complex geotechnological structure that requires certain (and sometimes quite cumbersome) effective measures to maintain them in a certain working condition. Here, great attention should be paid to the needs of high rates of wellbore deepening [13]. In order to fulfil the specified criterion, it is necessary to create rational conditions for a stable flow of a rock breaking process with restrictions concerning the resource of the effective tool operation.

In the context under consideration, several approaches to optimization of percussive rock breaking can be mentioned, i.e.: use of a drilling tool with increased wear resistance (this includes a tool equipped with ultra-hard materials); use of the principles of toolless rock mass breaking (physical and chemical methods of rock disintegration are a characteristic feature of the case under consideration); involvement of highly mobile elements in the interaction with a wellbore with the possibility of their operational circulation replacement (principles of combined ball jet drilling are traced here); creation of certain conditions to intensify downhole breaking processes due to dynamic impact of a special tool (a drilling tool layout includes the machines generating shock pulses of different amplitudes and frequencies) [5].

A drilling tool made with the use of relatively wear-resistant cutting structures, is distinguished, for the most part, by a rather high cost, determined not only by a significant indicator of the consumable costs but also by the complexity of the technological manufacturing of tool structures. That is also complicated by special requirements for bottomhole operation of the latter. It narrows somewhat the area of possible rational use of such a drilling tool and requires preliminary analytical and laboratory studies regarding the expediency of its use in specific lithological variants of rocks [1].

In terms of limited funding for drilling operations and the need to construct wells in complicated geological conditions, other considered approaches to the optimization of bottomhole rock breaking, separately or in a complex combination, are seen as the most acceptable ones from many leading positions.

Further developments were based on a rational technological approach, meaning implementation of significant dynamic loads on the wellbore using a hydraulic energy source. That makes it possible to obtain the mode of well deepening characterized by the intensive formation of zones of rock mass breaking and re-breaking of a very effective volumetric nature [14]. It is possible to create such conditions due to the involvement of metal balls that move with the flow of washing fluid at high speeds and impact the rock downhole. According to the features of the methodology of a briefly described modernized principle of ball jet drilling, metal balls also perform the work of processing the peripheral wellbore areas together with the percussion machines under certain technical and technological regulations [5].

The considered combined drilling method was studied rather comprehensively by means of analytical and bench modelling. The following can be noted among its main results: the method is characterized by active development of breaking deformations in the form of cracks and holes; the method is characterized by a clear dependence of the scale of breaking processes on the application of axial load and its subsequent physical results (compared to cases of rock breaking in the absence of dynamism of axial load application). This is illustrated both qualitatively and quantitatively on the corresponding graphs in figure 1 and figure 2.

The developed ball jet or hydromechanical method is distinguished by its exceptional feature – it is the possibility of obtaining a wide range of load application speed v, which is known to determine usefully the effectiveness of breaking processes. Along with a gradual increase in v values, there is a natural increase in the scale of breaking process development, followed by the formation of corresponding breaking and re-breaking zones.

The data shown in figure 1 demonstrate clearly that the penetration depth of breaking disturbances h into the rock mass, in comparison with the case of static application of axial load, increases by approximately 1.3-1.4 times. Certain dependence of the results of breaking processes on the petrophysical characteristics of rocks was also revealed. In this case, influence of a mineral grain size can be observed (constant fluctuations between the absolute values of the depth of breaking hole formation h within the range of 6-14% is noted here), which is necessary to take into account while developing regulations for the operation of designed drilling devices for hydromechanical well drilling.

Pre-qualification studies of the devices under consideration have proved that they exclude

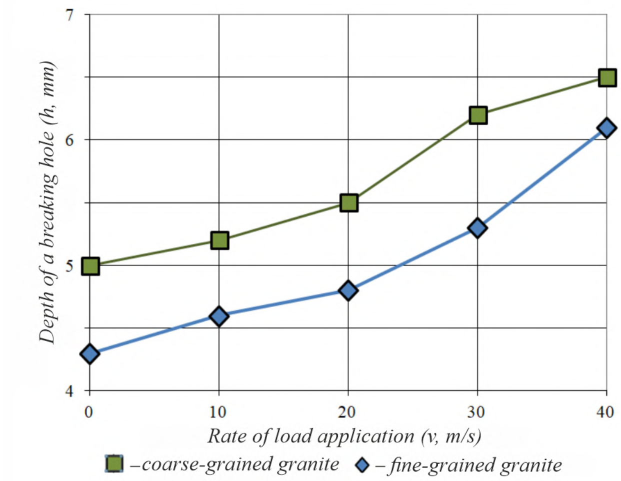

Figure 1. Patterns of the development of breaking processes for different mineralogical rock types under variable values of the axial load application rate.

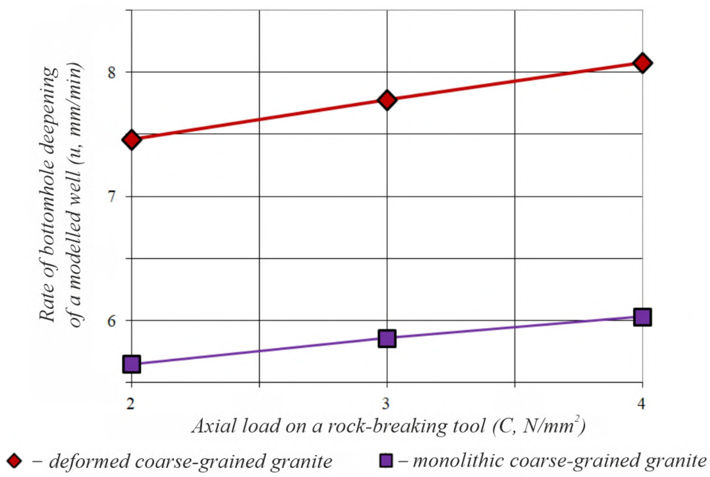

Figure 2. Influence of a physical state of rock mass on its breaking rate in terms of a modernized ball-jet method of well construction.

completely the most influential shortcoming of the ball jet drilling method – lack of proper treatment of the peripheral well zone. This is solved by complementing the device layout with a special design of rock-breaking organs, which, together with balls, form a well drilling contour. The effectiveness of this approach is the availability of an additional component in the complex downhole layout of a concrete hydromechanical drilling device. It allows forming the combined impact pulses on the rock mass deformed by active impacts of balls.

Under the proposed technical-technological scheme of drilling, there is a potential possibility of total exclusion of the suspension of well borehole deepening due to its complex curvilinear narrowing in the bottomhole part. Proper conditions for wellbore deepening are formed by the device rotation together with a rock-breaking organ and by creating the necessary static axial load with an active dynamic component (figure 2).

Thus, analyzing the data of figure 2 and statistics of the parametric values of stand studies, the following can be stated: by systematic increase in the rotation frequency n and axial load C, together with their reinforcement with dynamic pulses, it is possible to increase wellbore deepening rate u by approximately 30%. This is most clearly seen for a deformed bottomhole; in this case, growth of u is more than 40%.

A modernized ball-jet (hydromechanical) method of rock mass breaking (or abrasive-mechanical percussion method of rock breaking as we call it according to its technological essence), is the one that allows achieving high wellbore depth values, i.e. the main indicator that is the main criterion for the excellence of drilling operations; it is identified by a mechanical speed of drilling wells.

For its organic implementation in drilling practice, the method we have modernized does not require any significant technical and technological innovations and changes in the currently used layouts of the available drilling machines, mechanisms, tools etc. [15].

The design of a downhole rock-breaking tool adapted to the processing mode of the peripheral well zone is characterized by simple modification and work cycle stability. In addition to its simplicity, a ball jet device needs only some special hydraulic mode of operation; that was taken into account as much as possible while developing an additional percussion machine for it – a modernized hydraulic hammer [16]. In addition to the necessary clear synchronization of the interaction with a jet device, the reasons for its improvement included following significant defects peculiar for the majority of currently operated impact machines, i.e.: excessive complexity of the functioning of components and parts in a "valve-piston-hammer" system with the lack of sufficient technologically substantiated range of movement speeds of the latter. This provokes considerable and unpredictable, in terms of absolute values, pressure fluctuations in the device, reducing significantly the energy intensity of each individual act during the shock pulse generation. In most cases, hydraulic shock devices are also characterized by large alternating loads on power springs with their active wear and failure.

Figure 3 demonstrates a general scheme of the proposed hydraulic hammer, which includes: an upper locking adapter 1 with an internal thread 2 for the column nipple and recesses 3 for a drilling tongs as well as a central circulation channel 4. An adapter 1 with a casing bushing 24 connected by a thread 29 form an acceleration chamber 5. Casing bushings 24 and a cup 18, connected by a thread 31, form an impact chamber 8. In the internal part of the interconnected adapter 1, the casing bushing 24, and the acceleration chamber 5, the following operates: hammer 7, which contains a high-pressure pneumatic chamber 19, a through circulation channel 6, a drainage channel 26 with the circulation holes 25, rubber-metal sealing rings 27, and an anvil 11, which contains through holes 9 and a central circulation channel 10, external splines 16, shank adaptor 20, and sealing elements 21, 22, 28. To remove the washing liquid, the casing bushing 24 contains resettable circulation windows 23. A casing cup 18 in its lower part is equipped with internal splines 17 for the connection with the anvil 11, which also contains a metric thread 15, to which the lower adapter 12 with the recesses 31 for drilling tongs, a vertical circulation channel 13, and a tool-joint thread 14 are connected.

When lowering the hydraulic hammer in combination with the jet machine, with mandatory flushing fluid circulation when reaching the wellbore, the fluid moves as follows: the central circulation channel 4 of the lock adapter 1, the acceleration chamber 5, the through circulation channel 6 of the hammer 7, the impact chamber 8, the through holes 9, and the central circulation channel 10 of the anvil 11, the vertical circulation channel 13 of the lower adapter 12. When the assembly connected to the locking thread 14 of the lower adapter 12 reaches the wellbore, the axial movement of the adapter 12 and the anvil 11 connected to it by the metric thread 15 occurs, which unhindered and stable movement is ensured by the contact of the splined pair "outer splines 16 of the anvil 11- inner splines 17 of the casing cup 18". The occurrence of a hydraulic shock – a generator of shock pulses of the corresponding frequency, occurs when the anvil 11 is moved axially by a structural parametric value L, which overcoming leads to an instant increase in the liquid pressure in the acceleration chamber 5, being the result of blocking the liquid flow to the bottomhole with the help of through holes 9 in the anvil 11, which, together

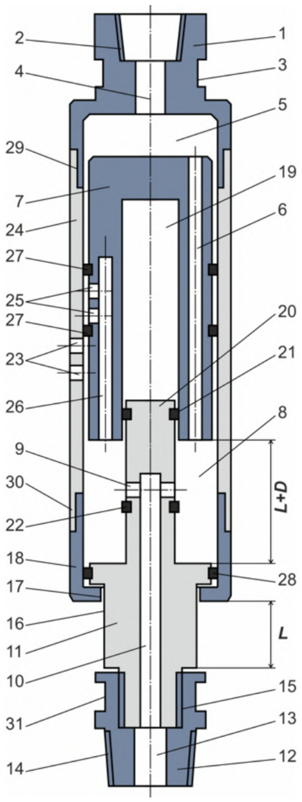

Figure 3. Layout diagram of a hydraulic hammer device.

with the shank adaptor 20, are immersed in the high-pressure pneumatic chamber 19 of the hammer 7. The consequence of the indicated interaction will be the rapid accumulation of the necessary kinetic energy reserve by the hammer 7, which will cause it to impact the anvil 11 with a given working movement by distance D.

The accuracy of impacting the anvil 11 is ensured by the anisobaric nature of the processes in the high-pressure pneumatic chamber 19, filled with compressed gas with a critical pressure of $P \geqslant 0.4$ MPa and its periodic compression (during the active washing liquid movement) or expansion (when the active movement stops), which corresponds to a specific stage of the circulation process in the acceleration chamber 5. Hermeticity of the high-pressure chamber 19 and insulation of the through holes 9 in the anvil 11 is ensured by the rubber-metal sealing rings 21 and 22. Constancy of the processes of forward and reverse movements of the hammer 7 is possible while fulfilling the conditions for flushing liquid removal from the impact chamber 8 by synchronizing the location of the resettable circulation windows 23 of the casing bushing 24 and the circulation holes 25 made in the drainage channel 26 of the hammer 7. The rubber-metal sealing rings 27 exclude unpredictable connection of the circulation holes 25 of the drainage channel 26 with the circulation windows 23 of the casing bushing 24. Smoothness and isolation of the movement between the pair of "external splines 16 of the anvil 11 – internal splines 17 of the casing cup 18" and the casing cup 18 itself is ensured by the sealing element 28. The technological manufacturing of the hydraulic hammer structure and the possibility of its maintenance are also facilitated by the available threaded connections 29 and 30 between the upper lock adapter 1, casing bushing 24, and casing cup 18, respectively. The installation operations with the lower adapter 12 are convenient as there is the recess 31 for the drilling sickle-shaped tongs on its surface. The principle of hydraulic hammer operation in the automatic mode and possible adjustment of the latter are based on the creation of a regular periodic flushing fluid circulation for the hydraulic hammer, which can be achieved by operational transformation of the drilling pump design – a combination of the technological scheme of operation and interaction of plungers, disconnection of a compensator, and modernization of the piston operation cycle.

An abrasive-mechanical impact method is the one that it allows its versatile technological enhancement. Since the basis of the operation of the drilling machines accompanying its technological cycle is transformation of hydraulic energy, which is supplied in the form of a directed flow of flushing fluid, it is important here to preserve maximally the original characteristic hydraulic parameter of the flow – pressure drop (produced by the surface drilling pump) to overcome the resistances in the circulation circuit of the drilling well, i.e. in the percussion machines themselves [17].

Special experimental studies were conducted at the Department of Oil and Gas Engineering and Drilling of Dnipro University of Technology. Their purpose was to clarify the patterns of influence of surface-active substances (surfactants) and polymer additives on hydraulic supports during the movement of liquid through a pipeline [18]. These studies were performed on a special stand (figure 4), where pressure drop ΔP was measured in a standard steel pipe with a diameter of 14 mm and a length of $L = 4.5$ m, through which the NB-11E pump pumped the studied liquids at different speeds (they were controlled with the help of a valve, marked as B in the diagram, figure 4). DT-10 pressure sensors (marked as M_1 and M_2 in the diagram, figure 4), VT-21 equipment complex, and an oscilloscope were used to measure pressure and determine its difference for the solutions and without surfactants and polymer additives at the tube inlet and outlet [19].

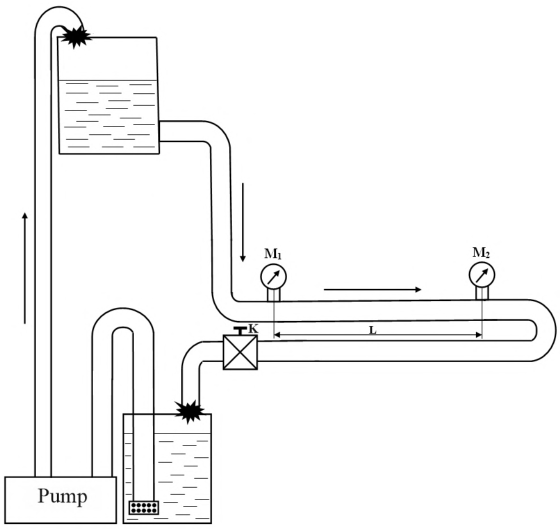

Figure 4. Schematic diagram of a laboratory stand to study hydraulic resistances when pumping liquid through a pipeline.

The next analytical stage of the research involved determining the value of resistance reduction to liquid movement through a pipeline (in%) [20], which we called hydraulic efficiency A calculated according to following formula

$$A = \left(\frac{\Delta P_0 - \Delta P_A}{\Delta P_0}\right) 100\%, \tag{1}$$

where ΔP_0 is drop in liquid pressure at the pipe ends without adding active impurities to the circulating medium; ΔP_A is pressure drop at the pipe ends due to addition of polymers and surfactants to the circulation medium.

Table 1 represents summary data on the determination of a generalized coefficient of hydraulic resistance and so-called hydraulic efficiency A.

Table 1. Influence of surfactants and water-soluble polymers on the values of a generalized coefficient of hydraulic resistance and hydraulic efficiency.

Active additive	Admixture concentration, %	Generalized coefficient of hydraulic resistance	Efficiency A, %
Sulphate soap	0.5 | 1.0 | 2.0	0.031 | 0.027 | 0.027	0 | 12 | 12
Ditalan	0.5 | 5	- | 0.018	- | 42
Metaupon	0.5	0.024	22
Polyacrilamid	0.01 | 0.05 | 0.10	0.027 | 0.017 | 0.015	12 | 44 | 52
Polyoxyethylene	0.005 | 0.010	0.015 | 0.015	58 | 58
Polyacrylonitrile	0.05 | 0.10 | 0.5	0.027 | 0.026 | 0.020	12 | 12 | 35
Polyacrilamid+sulphate soap	0.05 | 0.5	0.015	52
Polyacrilamid+tall oil+OP-10	0.05 | 0.5 | 0.25	0.015	52

While analyzing the data represented in table 1, following conclusions can be drawn: polymer additives and surfactants within a certain range of concentrations reduce hydraulic resistance but the degree of this effect depends on the polymer and surfactant types [21]. The greatest reduction of hydraulic resistances can be obtained with the use of polyacrylamide and polyoxyethylene additives. Moreover, it was found that plant polymers lose their effectiveness during the circulation through a pipeline as a result of so-called destruction of molecules, which is evidenced by a decrease in the solution viscosity. To maintain the duration of the effect of hydraulic resistance reduction, it is necessary to use polymers in combination with additives of special reagents-stabilizers [22].

In general, the task of planning an effective hydraulic washing programme means development of compositions and technology for preparing such washing liquids, which would have simultaneously the following most important properties: reducing the coefficient of internal friction, thereby reducing hydraulic resistance; decreasing the surface tension; reducing the manifestation of friction effect during the rotation and contact of a drillstring and a rock-breaking tool with the rock due to lubrication; and preventing swelling, wetting, and falling of clayey and other unstable rocks.

A significant and still insufficiently used reserve of intensification of downhole breaking processes [23] in terms of simultaneously decreasing power losses for the technologically necessary rotation of a drillstring in the wellbore (table 2) is in the possibility to use special flushing fluids treated with appropriate active reagents of complex effect.

Basing on the analysis of the experimental data shown in table 2, it can be stated reasonably that, of all the considered substances, the greatest reduction in the friction coefficient can be obtained when tall oil is added into the drilling fluid [24].

Since it is established and proven that a decrease in the surface tension of flushing fluids σ [25] contributes to the increased mechanical speed of drilling, complex studies were conducted to clarify the nature of the influence of active components on the technological properties of flushing fluids and the results of breaking processes in their application. The data on the laboratory-stand studied of these issues are represented in figure 5 and figure 6. The change in σ indicators must be considered in the context of complex effect of surfactants on the properties of washing liquids with the corresponding consequences.

Table 2. Results of studying the influence of various active additives in flushing fluids on a steel-rock friction coefficient (simulation of well rotational movement of a drill string).

Active additive (Name)	Active additive (Concentration, %)	Coefficient of friction on rocks (Sandstone)	Coefficient of friction on rocks (Argillaceous slate)
Water (Soap stock)	- | 0.5 | 1.0 | 2.0	0.52 | 0.18 | 0.12 | 0.11	0.40 | 0.34 | 0.23 | 0.15
Water (Sulfonol)	0.25 | 0.50 | 1.00	0.26 | 0.19 | 0.19	0.35 | 0.26 | 0.25
Water (Tall oil)	0.25 | 0.50 | 1.00 | 2.00	0.13 | 0.11 | 0.11 | 0.11	0.29 | 0.15 | 0.14 | 0.14
Clay mud of bentonite powder (Bentonite powder)	10.0	0.55	0.46
Clay mud of bentonite powder (Soap stock)	0.50 | 1.00 | 2.00	0.54 | 0.54 | 0.53	0.42 | 0.42 | 0.41
Clay mud of bentonite powder (Sulfonol)	0.25 | 0.50 | 1.00	0.25 | 0.53 | 0.52	0.46 | 0.46 | 0.45
Clay mud of bentonite powder (Tall oil)	0.25 | 0.50 | 1.00 | 2.00	0.32 | 0.23 | 0.21 | 0.16	0.27 | 0.21 | 0.20 | 0.20

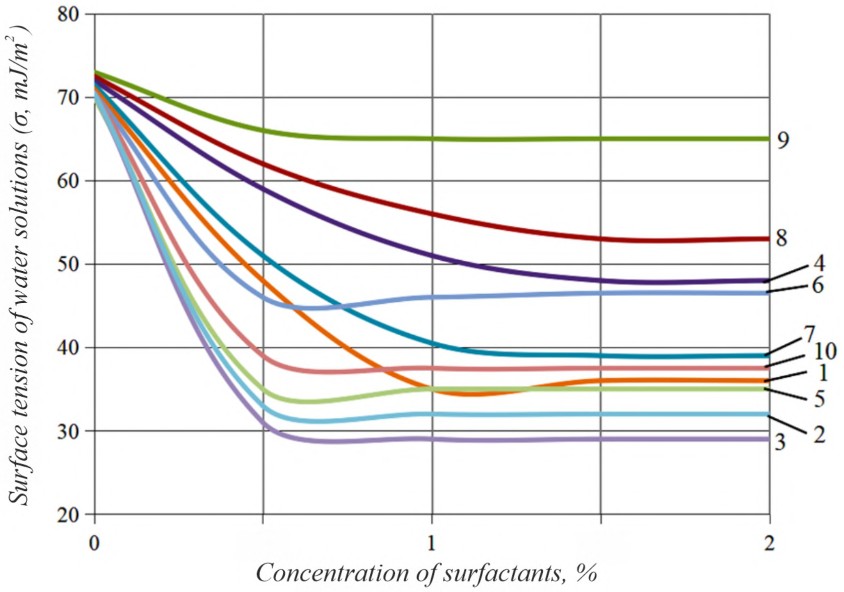

Figure 5. Experimentally determined dependence of surface tension σ of water solutions on the surfactant concentration: 1 – tall oil; 2 – tall oil + sulfonol; 3 – sulfonol; 4 – emulsol; 5 – sulfate soap; 6 – ditalan; 7 – mixture of tars; 8 – katapin; 9 – hydro processed oil sludge; 10 – HFA.

According to the complex experimental data shown in figure 5 and figure 6, following conclusions can be made: when processing washing liquids (in this case, technical water) with the studied surfactants, a decrease, sometimes quite significant, in surface tension σ [26] by 10-240% is observed, and such a transformation of σ indicator is noted in the concentration range of 0.5-1% surfactant (figure 5) [27]. Use of flushing fluids with a reduced σ index during the

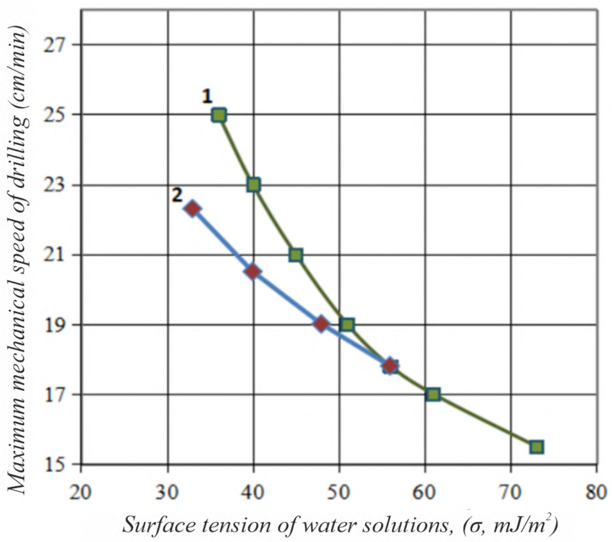

Figure 6. Dependence of the mechanical speed of drilling on surface tension σ of flushing fluids: 1 – percussive rotary drilling; 2 – rotary drilling.

rock mass breaking results in the increasing maximum possible mechanical speed of drilling by the basic 1.6 times for percussive-rotary drilling and by 1.3 times for the rotary method of well construction (figure 6) [28].

The considered technical solutions have a relatively simplified implementation, which, however, did not cause any violations of the completeness of a shock pulse generation cycle [29]. The above also concerns the use of special washing liquids with the activation of some of their general and special functional properties [30].

4. Conclusions

The perspective of thorough analytical development and wide industrial implementation of an innovative abrasive-mechanical impact method of obtaining suitable rock products is shown in the context of the need to increase a well construction rate along with simultaneous reduction of financial and material costs for drilling technological and, immediately, rock-breaking tools. Distinctive features of the specified method are that it requires the use of a special type of rock-breaking elements (in the form of special-design drill crowns and metal hard-alloy balls) as well as jet and percussion hydraulic machines. Such a comprehensively formed bottomhole layout allows intensifying and strengthening significantly the breaking processes and phenomena for rock mass. It can be characterized by current significant technologically controlled development of deformation disturbances in the form of cracks and rock chipping.

There are following particular components to regulate well deepening with the help of balls: speed of applying ball load v to the well bottomhole and axial load C on them during their subordinate movement in the peripheral zone of the well bottomhole. The results of breaking processes make it possible to confirm that the method under consideration demonstrates an increase in the mechanical drilling speed u by a weighted average of 20-30% and an increase in the volumes of breaking zones by 2 or more times in comparison with the corresponding values obtained for the case of static application of axial forces.

The paper represents a technical description of the percussion machine, which can be adapted especially to the conditions of implementation of the abrasive-mechanical percussion method.

The conducted studies show the prospects of using surfactants and polymers as hydraulic resistance reducers (up to 50% or more) in the circulation contour of the well, which will contribute to the additional strengthening of the effect of active washing liquid jets on the rock mass. The use of specified chemically active reagents as a component of flushing fluids also helps reduce significantly the power consumption for drill string rotation in the wellbore by minimizing a coefficient of friction (depending on the type of rocks and flushing fluids, it can be reduced by 1.1-4.0 times and even more). Treatment of flushing fluids with certain surfactant also contributes to the reduction of their surface tension σ, which has a positive effect on the results of destructive processes (due to this, it is possible to increase the mechanical drilling speed by a minimum of 30%, especially the indicated case relates to the technological reception of shock impact on the bottomhole).

Acknowledgments
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References

[1] Guan Z, Chen T and Liao H 2021 *Theory and Technology of Drilling Engineering* (Singapore: Springer) URL https://doi.org/10.1007/978-981-15-9327-7
[2] Guo B, Lyons W C and Ghalambor A 2007 *Petroleum Production Engineering: A Computer-Assisted Approach* (Gulf Professional Publishing) URL https://doi.org/10.1016/B978-0-7506-8270-1.X5000-2
[3] Guhey R 2017 *Geology* (NIPA)
[4] Dareing D W 2019 *Oilwell Drilling Engineering* (ASME Press)
[5] Ihnatov A 2021 *Mining of Mineral Deposits* **15**(3) 122–129 URL https://doi.org/10.33271/mining15.03.122
[6] Islam M R and Hossain M E 2020 *Drilling Engineering: Towards Achieving Total Sustainability* Sustainable Oil and Gas Development (Gulf Professional Publishing)
[7] Pavlychenko A V, Ihnatov A O, Koroviaka Y A, Ratov B T and Zakenov S T 2022 **1049**(1) 012031 URL https://doi.org/10.1088/1755-1315/1049/1/012031
[8] Biletsky M T, Kozhevnykov A A, Ratov B T and Khomenko V L 2019 *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu* (1) 21–27 URL https://doi.org/10.29202/nvngu/20191/22
[9] Hossain M E and Islam M R 2018 *Drilling Engineering Problems and Solutions: A Field Guide for Engineers and Students* (Wiley - Scrivener Publishing)
[10] Caenn R, Darley H C H and Gray G R 2020 *Composition and Properties of Drilling and Completion Fluids* (Gulf Professional Publishing) URL https://doi.org/10.1016/C2015-0-04159-4
[11] Jeffery W H 2015 *Deep Well Drilling: The Principles and Practices of Deep Well Drilling* (Palala Press)
[12] Biletskiy M T, Ratov B T, Khomenko V L, Borash B R and Borash A R 2022 *News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences* **2022**(5) 51–62
[13] Ratov B T, Fedorov B V, Khomenko V I, Baiboz A R and Korgasbekov D R 2020 *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu* **2020**(3) 13–18 URL https://doi.org/10.33271/nvngu/2020-3/013
[14] Ihnatov A O, Koroviaka Y A, Pinka J, Rastsvietaiev V O and Dmytruk O O 2021 *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu* (1) 11–18 URL https://doi.org/10.33271/nvngu/2021-1/011

[15] Lopez Jimeno C, Lopez Jimeno E and Ayala Carcedo F J 1995 *Drilling and Blasting of Rocks* (Taylor & Francis)
[16] Kyelgyenbai K, Pysmennyi S, Chukharev S, Purev B and Jambaa I 2021 **280** 08001 URL https://doi.org/10.1051/e3sconf/202128008001
[17] Bansal R K 2010 *A Textbook of Fluid Mechanics and Hydraulic Machines* (Laxmi Publications)
[18] Kumar D S 2009 *Fluid Mechanics and Fluid Power Engineering* (S K Kataria & Sons)
[19] Benyoucef L 2020 *Reconfigurable Manufacturing Systems: From Design to Implementation* Springer Series in Advanced Manufacturing (Cham: Springer) URL https://doi.org/10.1007/978-3-030-28782-5
[20] Speight J G 2018 *Formulas and Calculations for Drilling Operations* 2nd ed (Beverly, MA: Scrivener Publishing) URL http://182.72.188.194:8080/jspui/bitstream/123456789/1449/1/Formulas%20and%20Calculations%20for%20Drilling%20Operations%20by%20James%20G.%20Speight.pdf
[21] Sharma K K and Sharma L K 2016 *A Textbook of Physical Chemistry* 6th ed (Vikas Publishing House)
[22] Dalal M 2018 *A Textbook of Physical Chemistry* vol 1 (Dalal Institute) URL https://www.dalalinstitute.com/books/a-textbook-of-physical-chemistry-volume-1/
[23] Zhang Z X 2016 *Rock Fracture and Blasting: Theory and Applications* (Butterworth-Heinemann) URL https://doi.org/10.1016/C2014-0-01408-6
[24] Jadhav S 2015 *Oil & Gas Production* (Scitus Academics)
[25] Birdi K S 2010 *Surface and Colloid Chemistry: Principles and Applications* (CRC Press)
[26] Guo B, Liu X and Tan X 2017 *Petroleum Production Engineering* 2nd ed (Gulf Professional Publishing)
[27] Atkins P and de Paula J 2006 *Atkins' Physical Chemistry* 8th ed (New York: W. H. Freeman and Company) URL http://www.rnlkwc.ac.in/pdf/study-material/chemistry/Peter_Atkins__Julio_de_Paula__Physical_Chemistry__1_.pdf
[28] Ouadfeul S A and Aliouane L 2020 Introductory Chapter: Oil and Gas Wells - Advances and New Challenges *Oil and Gas Wells* ed Ouadfeul S A and Aliouane L (Rijeka: IntechOpen) chap 1 URL https://doi.org/10.5772/intechopen.90690
[29] Aadnøy B S and Looyeh R 2012 *Petroleum Rock Mechanics: Drilling Operations and Well Design* (Gulf Professional Publishing) URL https://doi.org/10.1016/C2009-0-64677-8
[30] Vaddadi N 2015 *Introduction to Oil Well Drilling: A layman's guide to the fascinating world of Oil exploration* (Bathos publishing)

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Component composition of the processed forming mixture and mineralogical recommendations for its re-use

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Component composition of the processed forming mixture and mineralogical recommendations for its re-use

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Abstract. Modern industrial production is aimed at the development of waste-free technological processes, wider use in the production of waste and by-products. The largest amount of waste is generated from the activities of mining and metallurgical enterprises. One of the problems of foundry production is the disposal of multiton solid waste, about 90% of which is spent molding mixture. Part of the spent mixture is reused as recyclable, but the main mass of it is collected at municipal solid waste landfills. This work is devoted to the study of the component composition of foundry production waste – spent molding mixture with the aim of its reuse. According to the results of the research carried out by the authors, mineralogical recommendations regarding its reuse were provided. Involvement in the reuse of spent molding mixture will allow to free up part of the solid household waste landfills, reduce the negative man-made load on the environment, and additionally obtain conditioned restored molding sands.

1. Introduction

Currently, Ukraine has accumulated about 45 billion tons of industrial waste, located on an area of more than 160,000 hectares. About 1.7 billion tons of new waste is generated every year, while 5-12% of waste is reused, while in developed countries industrial waste is used for 60-80% [1–3].

The largest amount of waste is generated from the activities of mining and metallurgical enterprises. One of the enterprises that uses the metallurgical cycle of processing raw materials is the Kryvyi Rih Repair and Mechanical Plant (Metinvest – KRMZ LLC) in the city of Kryvyi Rih, the main activity of which is the production of machines and equipment for the mining and mining processing industry, parts and components for it, as well as production of steel and iron castings, welded metal structures, stampings, non-standardized equipment for objects under construction or reconstruction. This enterprise includes a full production cycle, from metal smelting to the production of finished products in the form of machines and mechanisms.

The main waste of the enterprise, which can be involved in processing, is generated in the steel casting, mechanical assembly, repair and tool shops, and metal structures shop [4, 5]. The waste of these subdivisions includes: dust from gas cleaning traps (emissions from electric steel melting furnaces in the form of suspended particles undifferentiated by composition), foundry slag, slag, spent molding mixture, welding production waste, abrasive metal dust. Welding production waste and slag are completely disposed of at the enterprise for internal needs, all other generated waste is processed by the enterprise for its own needs in small quantities, and the main volume is transferred to third-party organizations or stored on the factory territory. One of the problems of foundry production is the utilization of multi-tonnage solid waste, about 90% of which is spent molding mixture, which currently belongs to substances of the 4th category of danger [6–8]. A part of the spent mixture is reused as a turnover, for the Kryvyi Rih Repair and Mechanical Plant, this indicator is 10percent of its total mass. The rest is collected at municipal solid waste landfills.

2. Methodology

The current state of production waste was analyzed and compared with global trends. Waste samples were selected by the authors. Chemical analyzes were carried out, granulometric and component composition and the content of impurity elements were investigated. The current state of the situation with industrial waste was analyzed and compared with global trends.

Detailed mineralogical studies of spent molding mixture waste (burnt earth) were carried out. According to the results of the obtained data, mineralogical recommendations for the technological scheme of the processing of the used molding mixture and its reuse are provided.

3. Results

The authors investigated the waste of the steel foundry shop – spent molding mixture (burnt earth), which is formed from foundry molds and rods during the production of metal blanks. After knocking out hardened castings from foundry molds on grids and sieving on sieves, metal blanks and waste are obtained in the form of burnt molding mixture. According to the technological regulations of the Kryvyi Rih Repair and Mechanical Plant, about 10% of the mixture is reused, the rest is transported by road transport to the temporary storage site (figure 1).

Figure 1. Site of temporary storage of industrial waste.

Based on the results of granulometric, chemical, and detailed mineralogical studies of the composition, structure, and texture of the used molding mixture by the authors, it was established:

- The spent molding mixture was represented by a loose, lumpy material of burnt sands of gray, dark gray to black color with a brownish, yellowish tint.

- The structure of the material is psammitic with a minor psephytic component content (figure 2).
- The size of the lumps varies from 1 to 10-20 cm, with mechanical action the lumps are destroyed.

Figure 2. The material of the spent molding mixture.

The lumpiness of the mixture (figure 3) is due to significant heating of the molding mixture during the pouring of the molds. The presence of a metal component (hooks, nails, forming pins) in the spent mixture is associated with their use as an auxiliary material in the assembly of casting molds. After knocking out on the grates, part of the hooks, nails, and forming pins remains in the mixture and falls together with the burnt sand to the temporary storage area.

(a) (b)

Figure 3. Lumpy particles (a) of the molding mixture with individual metal inclusions and metal pins (b) in its composition.

During the selection of initial samples, in addition to the above-mentioned metal objects in the composition of the used molding mixture, individual allocations of residual metal in the form of “beads”, dendrites, and irregular shapes were occasionally observed. The size of the discharges ranged from 1 to 10-20 cm. Large fragments are most often manually selected by the employees of the enterprise from the composition of burnt earth, were identified by the authors during the selection of initial samples at the enterprise and did not fall into the composition of the examined samples of burnt earth (figure 4).

(*a*) (*b*)

Figure 4. Separation of residual metal in the spent molding mixture.

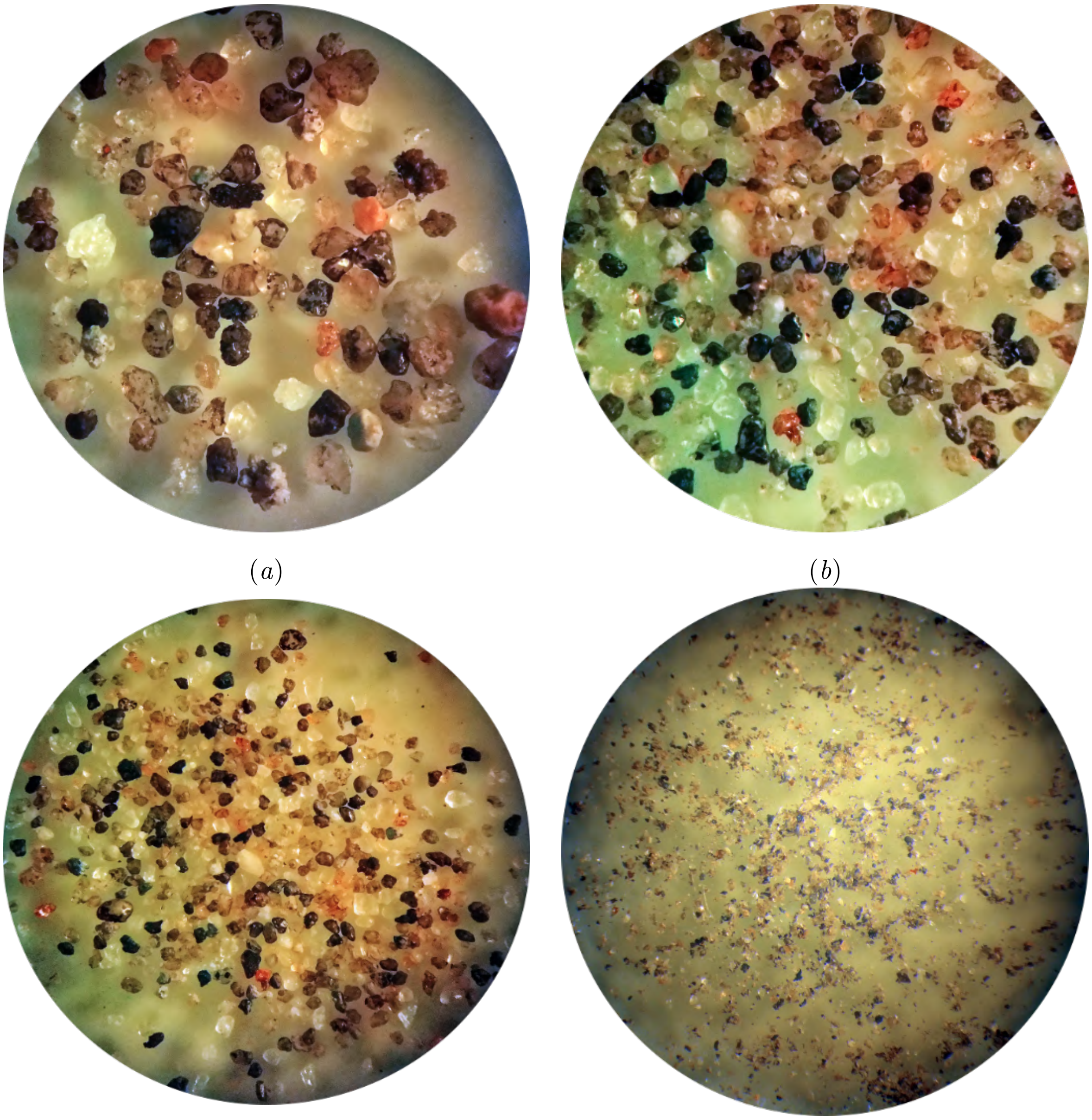
The authors established that the average content of coarse-grained material (particles larger than 0.5 mm) in the composition of burnt earth is 5.1%, the main part of the material (85.4%) is represented by particles with a size of -0.5+0.1 mm. The amount of the most fine-grained (siltstone-pelitic) component is 9.5% (figure 5).

Mineralogical studies were performed by the authors using macroscopic and microscopic methods. According to the results of detailed mineralogical studies, the average component composition of the used molding mixture was determined (table 1).

Table 1. The average component composition of the spent molding mixture.

Components	Content
quartz	91.6
carbonates	0.9
metal component	0.9
oxides and hydroxides of iron	0.4
Total	100.00

The results of a complete silicate analysis obtained by the authors for the material of the spent molding mixture revealed that the product-forming chemical component is silica, aluminum, iron and calcium oxides are of secondary importance (table 2).



(*a*) (*b*) (*c*) (*d*)

Figure 5. Material of selected granulometric fractions of burnt earth: (*a*) granulometric fraction +0.5 mm; (*b*) -0.5+0.25 mm; (*c*) -0.25+0.1 mm; (*d*) -0.1+0 mm.

The significant content of silicon oxide is due to the presence of quartz as the main mineral component in the molding mixture. The increased content of aluminum oxide is associated with the presence of silicates – products of thermal effects on the clay minerals of the primary molding mixture. A noticeable admixture of calcium and magnesium oxides is due to the presence of carbonates represented by calcite and dolomite. The presence of iron oxides is caused by several factors: the presence of iron-containing minerals (magnetite, ilmenite, hematite, goethite, chromite) in the sand of the primary molding mixture; migration of iron from the molten metal to the side of the mold; the presence of iron in the composition of substances used to ensure the strength of forms, their non-stick properties, etc. The relatively high content of alkalis (sodium,

Table 2. The average content of chemical components in the spent molding mixture.

Chemical components	wt.%
SiO_2	83.09
Al_2O_3	6.22
Fe_2O_3	4.56
FeO	0.63
CaO	1.97
MgO	0.46
K_2O	0.05
Na_2O	0.69
P_2O_5	0.03
CO_2	1.43
S	0.06
H_2O	0.28
Insoluble residue	0.53
Total	100.00

Table 3. The average content of impurity elements in the material of the spent molding mixture.

Chemical elements	Average content impurity elements in the scorched earth mg/kg	Clarke number, mg/kg [9]	Clarke concentration
silver	0.067	0.07	0.96
bismuth	2.0	0.009	222.22
cobalt	6.0	18	0.33
chrome	1696	83	20.43
copper	30	47	0.64
germanium	2.0	1.4	1.43
manganese	2348	1000	2.35
molybdenum	7.0	1.1	6.36
niobium	10	20	0.50
nickel	62	58	1.07
phosphorus	570	930	0.61
lead	157	16	0.94
tin	4.0	2.5	1.60
titanium	4565	4500	1.01
vanadium	92	90	1.02
zinc	60	83	0.72
zirconium	248	170	> 1.46

to a small extent potassium) causes the use of liquid glass in the composition of the original molding mixture.

The content of rare, scattered chemical components in the used molding mixture was determined by the authors using the method of semi-quantitative spectral analysis (table 3).

The obtained data were compared with the data on the concentrations of the corresponding chemical components, which reflect the average content of each of them in the composition of the earth's crust. The authors assumed that the Clarke number corresponds to the safe concentration of the corresponding chemical element in both natural and man-made formations. In order to compare data on the average content of chemical components in the composition of burnt earth and their clarke, the Clarke indices of concentrations were determined – by dividing the values of the average content of an element by its Clarke number (table 3). According to the obtained data, all the investigated chemical elements can be divided into three groups:

(i) impurity elements, the content of which is less than clarke (clarke concentration lower than 1.0): silver, cobalt, copper, niobium, nickel, porcelain, lead, zinc;
(ii) elements, the content of which is close to the Clarke number (clarke concentration from 1.0 to 2.0): germanium, tin, titanium, vanadium, zirconium;
(iii) elements, the content of which in the composition of burned earth significantly exceeds the Clarke number (clarke concentration from 5 to 250): bismuth, chromium, molybdenum.

According to the authors, the reasons for significant fluctuations in the content of impurity elements in the material of the spent molding mixture compared to the amount of these elements can be as follows:

– the presence of the investigated impurity elements in the primary material of the molding mixture;
– the presence of these chemical elements in the composition of substances used to ensure the strength of forms, their non-stick properties, etc.;
– different behavior of chemical elements in the technological process (redistribution between the mold and the product, transition to the gaseous phase and evaporation, etc.).

The raw material used in the manufacture of casting molds mainly contains quartz sand and clay minerals (kaolinite, beidelite, hydromuscovite, etc.). They are characterized by a low isomorphous capacity, which is why the content of impurity elements in their composition is very low: for the studied chemical elements, it usually does not exceed 1 · 10-3 – 1 · 10-6 wt.%. The sand may contain accessory minerals, which include the studied chemical elements (ilmenite, chromite, zircon, monazite, rutile, pyrolusite, etc.).

In the process of preparing foundries molds, in accordance with the features of the technologies used, the following chemical components are added to the molding mixture: liquid sodium glass; soluble sodium silicate; lignosulfonate grade A; PLH-1 brand refractory clay; chromite concentrate; furan resin SQG-120; phenolic resin SQJ610; Permabind CO phenolic resin; phenol-formaldehyde resin NOVANOL 160, 165N; zirconium and magnesite non-stick mixtures.

Thus, in the composition of the components that are added to the clay-quartz molding mass, it is possible to distinguish:

– inorganic substances that practically do not contain the studied impurity elements (sodium liquid glass, refractory clay);
– organic substances that do not contain the investigated impurity elements (lignosulfonate, furan resin, phenolic resin, phenol-formaldehyde resin);
– mineral components, which include investigated impurities (chromite concentrate, zirconium and magnesite non-stick mixtures).

That is, in the composition of substances added to the molding mixture, there are two of the 36 investigated chemical components – chromium and zirconium. The technological process is accompanied by:

– partial combustion of organic substances (lignosulfonate, furan resin, phenol resin, phenol formaldehyde resin) with the formation of amorphous carbon present in the form of "shirts" on quartz particles and their cementing substance;

- sublimation of parts of impurity elements characterized by low melting and boiling (evaporation) temperatures: bismuth (melting point 271°C, boiling point, evaporation 1564°C), phosphorus (respectively, 44°C and 277°C), zinc (420°C and 907°C), ytterbium (819°C and 1194°C), strontium (769°C and 1382°C), thallium (304°C and 1473°C), lithium (18°C and 1342°C), stybium (630°C and 1587°C), mercury (-39°C and 357°C);
- redistribution of a part of refractory elements-admixtures (chromium, manganese, titanium, cadmium, molybdenum, cobalt, nickel, zirconium, tungsten) between the outer surface of the casting and the inner surface of the mold.

4. Conclusions

One of the problems of foundry production is the disposal of multiton solid waste, about 90% of which is spent molding mixture [10, 11]. The existing methods of using the spent mixture can be divided into three groups:

(i) use of spent molding mixture without additional processing;
(ii) methods that ensure processing and recycling of production waste at the same enterprise;
(iii) methods of processing and utilization of spent molding mixture in various branches of the national economy.

According to the results of the research carried out by the authors, the following mineralogical recommendations were proposed regarding the technology of processing the spent mixture for the purpose of its reuse:

- due to the presence in its composition of spent mixture of metal inclusions (forming pins, nails, particles of excess metal in the form of beads, dendrites, formations of irregular shape) it is necessary to remove them from the composition of the mixture; at the same time, it is necessary to take into account that individual metal particles can be weakly or non-magnetic;
- the spent molding mixture is a loose, lumpy material of the sand fraction with an admixture of psephyto-siltstone-argillite and pelite components. The lumpiness is due to the presence of impurities used in the preparation of the molding mixture and its significant heating and sintering during the pouring of the molds;
- when drawing up a technological scheme for the processing of the mixture, it is necessary to ensure the destruction of lumpy aggregations of the mixture, the rubbing of quartz particles from silicate-hydroxide “shirts”, the reduction of the number of binding organic and inorganic components on the surface of quartz particles to a level that will allow the separation of aggregations into separate particles;
- restoration (regeneration) of the spent molding mixture can be carried out using mechanical, hydraulic or pneumatic methods.

The spent mixture without preliminary processing can be used as an additive in the production of construction and road construction materials, it must first be cleaned of metal inclusions. In the production of silicate bricks, the spent mixture can completely replace quartz sand. The use of burnt earth will increase the degree of sintering of the brick mass due to liquid glass and alkalis in its composition. Using the spent molding mixture, you can get building solutions, wall stone, concrete products, cinder blocks, foam concrete.

The spent mixture without preliminary treatment can be used for reclamation of spent quarries, backfilling of road surfaces, in the technological processes of solid household waste landfills for overlapping layers as an insulating material in the middle and upper parts of landfills. In road construction, the spent mixture, classified as a special soil and classified as man-made soil (industrial waste), can be used as a component of the upper part of the road surface, for the formation of embankments.

Modern industrial production is aimed at the development of waste-free technological processes, wider use of waste in production and by-products. The reuse of spent molding mixture will allow to free up part of the solid household waste landfills, reduce the negative man-made load on the environment, obtain additional commercial products for third-party consumers, and additionally obtain conditioned reclaimed molding sands.

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References

[1] Khobotova E, Ignatenko M, Larin V, Kalmykova Y and Turenko A 2017 *Chemistry & Chemical Technology* **11**(3) 378–382 URL `https://doi.org/10.23939/chcht11.03.378`

[2] Bondarenko V and Filonenko O 2020 *Collection of research papers of the National Mining University* **61** 78–93 URL `https://doi.org/10.33271/crpnmu/61.078`

[3] Cioli F, Abbà A, Alias C and Sorlini S 2022 *Applied Sciences* **12**(13) 6420 ISSN 2076-3417 URL `https://doi.org/10.3390/app12136420`

[4] Doroshenko S P, Avdokushin V P, Rusyn K and Matsashek I 1990 *Forming materials and mixtures* (Vyshcha shkola, SNTL)

[5] Belobrov E A, Karpenkova O L, Volokita V Y and Voskovets V G 2013 On the problematic issues of the use of furan technologies in the production of steel castings in molds from cold steel production *Proceedings of the IV international scientific and technical conference* Promising technologies, materials and equipment in foundry production (Kramatorsk: DDMA) pp 23–29 ISBN 978-966-379-647-5

[6] Ivanova L K 2018 *Metal and casting of Ukraine* **304–305**(9–10) 65–67 ISSN 2077-1304

[7] Bublykov V B, Bachynskyi Y D, Yasynskyi O O, Medvid S M and Moiseyeva N P 2021 Elemental and Mineral Composition of ASH-Slag Wastes of Slovanska Thermal Power Plant *Proceedings of the VIII international scientific and technical conference* Promising technologies, materials and equipment in foundry production (Kramatorsk: DDMA) pp 26–27 ISBN 978-617-7889-00-6

[8] Bolshanina S B, Basov M V and Malovanyi M S 2014 *Visnyk Kremenchutskoho natsionalnoho universytetu imeni Mykhaila Ostrohradskoho* (4(87)) 175–179 URL `http://nbuv.gov.ua/UJRN/Vkdpu_2014_4_31`

[9] Alekseenko V A and Alekseenko A V 2013 *Chemical elements in geochemical systems. Clark soils of residential landscapes* (YuFU Publishing House) ISBN 978-5-9275-1095-5

[10] Liutyi R V and Huriia I M 2020 *Formuvalni materialy [Molding materials]* (KPI named after Igor Sikorsky) URL `https://ela.kpi.ua/handle/123456789/37398`

[11] Kuska P B, Nesterenko V V, Zverev V B and Chernyak A A 1991 *Building materials and products* (6) 5–10

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Implementation of sustainable development approaches by creating the mining cluster: the case of MPP "Inguletskiy"

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Abstract. The article provides the basic foundations of the implementation of sustainable development approaches in the world society and their interpretation in mining activities. The study also analyzes the regulatory framework and organizational mechanisms for the implementation of these principles in the Ukrainian mining industry. An analysis of the current state of rational subsoil use and solid industrial waste management in Ukraine is given. The concept of a mining cluster and prospects for its formation in the region of the Kryvyi Rih iron ore basin are substantiated. An algorithm designed to optimize the schedule of mining operations in the mining cluster is described. The Ingulets iron ore deposit was analyzed from the standpoint of integrated development. The reserves of talc shale extracted from the open-pit and stored in a man-made deposit for further sale are separately allocated. The order of mining works for the development of man-made deposits is given.

1. Introduction

The 1992 United Nations Conference on Environment and Development in Rio de Janeiro, also known as the "Earth Summit", announced a new paradigm for human development aimed at implementing sustainable development approaches. One of the results of the conference was the Declaration on Environment and Development, which is largely consistent with the principles of its predecessor – the Stockholm Conference of 1972, as well as its successor – the "Rio+20" Conference held in 2012 [1, 2].

The third principle of this Declaration emphasizes that the right to development must be exercised in such a way as to adequately meet the developmental and environmental needs of present and future generations [1, 2].

With regard to mineral resources, this principle directs society to solve the problem of providing them after the exhaustion of rich mineral deposits. In the context of the mining industry, this means that the slower new mineral deposits are brought into development, the more this principle will be fulfilled. And until humanity finds ways to industrially synthesize materials in sufficient volumes, comprehensive development of mineral deposits is the main direction of the implementation of the third principle of the UN Declaration on the Environment and Sustainable Development.

At the same time, the mineral and raw material base of Ukraine is quite significant on a global scale. Almost 20000 deposits and occurrences of 117 types of minerals have been discovered in the domestic subsoil, of which 8290 deposits and 1110 objects of accounting for 98 types of mineral raw materials are of industrial importance and are recorded in the state balance of mineral reserves, 3349 deposits are being developed [3–5].

The mineral and raw material complex of Ukraine provides a significant share of the gross national product. 48% of the country's industrial potential and up to 20% of its labor resources are associated with the mining industry and the subsequent use of minerals [6–8]. These indicators are quite comparable to the indicators of developed countries with a powerful mining industry. For example, the level of production waste utilization in the advanced countries of the world it reaches 80%. Such tendency of using of secondary resources has place in the Republic of South Africa, Japan, Canada, USA, Great Britain, France, Germany and other industrialized countries [9–11].

Today, in Ukraine numerous minerals are mined in Ukraine, such as coal (1.7% of total world production), commercial iron (4.5%) and manganese (9%) ores, uranium, titanium, zirconium, graphite (4%), kaolin (18%), bromine, ocher, non-ore metallurgical raw materials (quartzites, flux limestones and dolomites), chemical raw materials (native sulfur, rock and potassium salts), facing stone (granites, gabbros, labradorites), glass sand etc [12–14].

At the same time, the difficult economic situation does not allow geological exploration to be carried out sufficiently to reproduce the mineral and raw material base. Since 1994, the increase in explored reserves of most strategic types of minerals in Ukraine has not compensated for their extraction [3, 15].

There are a total of 54 iron ore deposits in Ukraine, of which 22 are in operation. Rich iron ores and iron quartzites are mined in the deposits of the Kryvorizka, Kremenchuk, and Belozirsk iron ore basins. Explored (confirmed) reserves amount to 28 billion tons, their share in the world's confirmed reserves (139 billion tons) is 20% [3, 16–18].

At the same time, the annual volume of waste in Ukraine only in the solid phase is 600 million m^3. 25 billion tons (8,6 billion m^3) of solid industrial waste accumulated to date are located on an area of more than 50000 hectares [19–21].

All this emphasizes the high relevance and paramount importance of the development of iron ore deposits of Kryvbas as a powerful mining complex of Ukraine.

2. Materials and methods

In order to determine how the provisions of the Declaration are implemented by mining enterprises of Ukraine, an analysis of the regulatory framework regulating their activities was performed.

Decree of the President of Ukraine dated July 23, 2021 No. 306/2021 implemented the decision of the National Security and Defense Council of Ukraine, which includes a list of metallic and non-metallic minerals that are of strategic importance for the sustainable development of the economy and the state's defense capability [14]. Iron ores are included in this list.

In the Law of Ukraine "On the approval of the State program for the development of the mineral and raw material base of Ukraine until 2030" [3], among the ways of solving existing economic problems, the "implementation of rational methods of development of complex deposits and extraction of associated components" is listed as one of the main steps to overcome crisis phenomena in the economy.

The Law of Ukraine "On Subsoil" [22], among the main principles of policy in the field of subsoil use, encourages users of subsoil to "rational, integrated use of subsoil ... to ensure the safety of the natural environment".

The Code of Ukraine on the Subsoil, among other things, defines the concept of man-made mineral deposits as "places where the waste of extraction, enrichment and processing of mineral raw materials has accumulated, the reserves of which are estimated and have industrial value" [22].

It is also noted that these deposits may arise as a result of losses during storage, transportation and use of mineral processing products. After the reserves of the man-made deposit have been assessed as industrial, it is included in the State Fund of Mineral Deposits, and all previously assessed mineral deposits are the reserve of this fund. In the same document, it is noted that the exercise of state control over the formation and use of man-made deposits and the processing of mineral raw materials is the responsibility of the Cabinet of Ministers of Ukraine. In turn, the procedure for state accounting of mineral deposits is regulated by the Resolution of the Cabinet of Ministers of Ukraine "On Approval of the Procedure for State Accounting of mineral deposits, reserves and occurrences": "...reserves of minerals are subject to accounting in the state balance sheet separately for each object (deposit, section of a deposit, mine field, etc.) according to the main industrial types, grades, brands, technological groups of minerals in accordance with current state standards, as well as according to the method of development, with allocation of reserves of raw materials suitable for extraction by underground, opencast, hydraulic and other methods" [23].

At the same time, it is obvious that in the long term, the development of man-made objects reduces the environmental load, but during the period of mining operations, the impact on the environment will be greater than from dumps in a re-cultivated state. And according to the law of Ukraine "On environmental impact assessment" "... it is prohibited to carry out economic activity... the use of man-made deposits of minerals, if the full observance of environmental conditions is not ensured" [24].

Carrying out an analysis of the legislator's base on how to develop man-made objects, showing the real imperfection that can be looked over. The above factors make it difficult to transfer man -made objects to the status of man-made deposits with their further development.

The measures laid down in the National Program provide for "...continuation of work on the formation of a database of man-made deposits of Ukraine" [3] and "...geological and economic evaluation of man-made deposits..." [3]. As a result of the implementation of the National Program for the Development of the Mineral and Raw Materials Base of Ukraine until 2030, it was planned to attract an additional 15 million tons of man-made raw materials from 2021 to 2030, that is very little on the scale of waste accumulated annually.

Solving the technological aspects of rational subsoil use begins with determining the schedule of mining operations, which would take into account all types of minerals that make up the deposit. For powerful operating enterprises, the question of choosing the main direction of development of mining works in most cases is already on the back burner, since there are restrictions on objects on the day surface, transport communications in the pit and the current situation of mining works [25–27]. However, the choice of the schedule of mining operations for subsidiary minerals, as well as the determination of the volumes of their extraction and storage in man-made deposits is still relevant. Moreover, variation of volumes and places of extraction is possible not only within the limits of separate mining enterprise, but of an entire mining cluster.

A cluster refers to a set of mining enterprises located in the same region and having stable technological, logistical, economic and financial connections among themselves. The identification of such clusters usually becomes possible when mining enterprises belong to the same owner. Then the market competition between such enterprises disappears and the connections outlined above strengthen. In turn, this strengthens the market positions of enterprises and significantly releases technological potential. The integration of enterprises in such clusters is initially appears in the simultaneous development of natural and man-made deposits with the management of a joint schedule of mining operations, and later – in the management of the schedule of mining operations and the productivity of the entire cluster of enterprises.

The Kryvyi Rih mining region is confidently moving towards the origination of such a cluster. This is confirmed by the purposeful formation of man-made deposits of subsidiary minerals, which takes place despite the difficult economic and technological conditions in the country.

3. Results

The Ingulets ferrous quartzite deposit, which is developed by the open-pit of MPP "Inguletskiy", is complex, since, in addition to the main mineral – magnetite quartzites, it also includes deposits of oxidized ferrous quartzites, manganese ore, granites, talc shale, limestone, etc (figure 1).

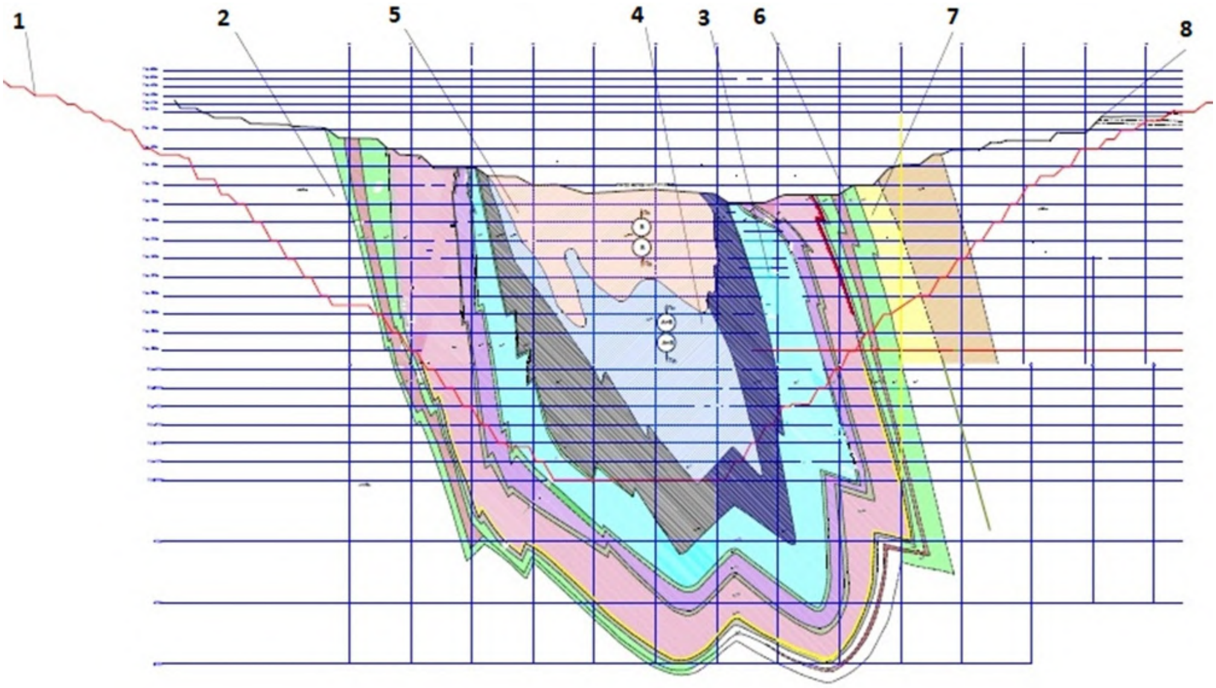

Figure 1. Geological section along surveying axis 70 of the pit of the MPP "Inguletskiy": 1 – project outline of the pit; 2 – migmatite; 3 – magnetite, silicate-magnetite quartzites; 4 – hematite-martite quartzites; 5 – oxidized quartzites; 6 – amphibolite-biotite schists; 7 – talc shale; 8 – the actual position of mining operations.

In addition, magnetite quartzite, which is the main useful mineral, is represented by seven grades of ore with different indicators of the content of the useful component and enrichment. This further complicates the separation of cargo flows by subsidiary minerals.

Moreover, the full realization of subsidiary minerals currently extracted from the open-pit is impossible without temporary storage. This is explained by the variability of demand for minerals and the complexity of managing the schedule of mining operations for them. The figure 2 shows the dynamics of current mining of granites and talc shale from 2013 to 2021. Therefore, there is a need for temporary storage of subsidiary minerals with the formation of temporary warehouses and man-made deposits.

At the same time, the following technological difficulties arise during the exploitation of man-made deposits:

- Selective placement of each type of subsidiary minerals requires alienation of large land areas.

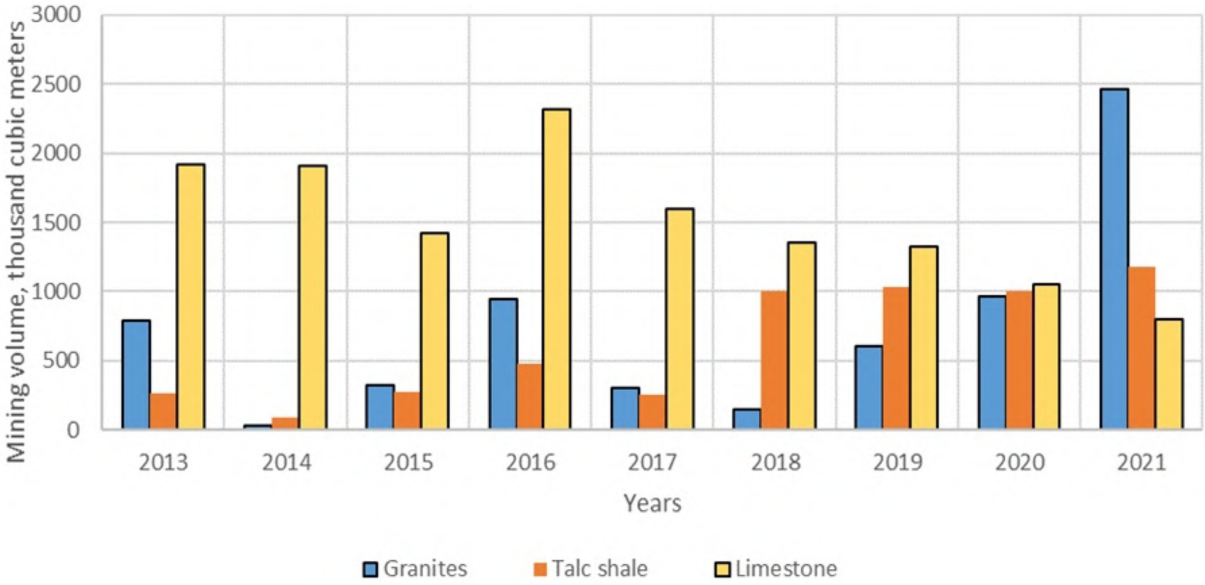

Figure 2. The dynamics of the production of transitory minerals in the open-pit of MPP "Inguletskiy".

- In fact, in the process of waste rock dump creating or storage of man-made raw materials, the accounting of its quality characteristics is not carried out in most cases, and the spatial placement is recorded inaccurately.
- Quantitative and especially qualitative characteristics of man-made raw materials can change over time under the influence of meteorological factors of the external environment (precipitation, groundwater, physico-mechanical and physical properties of the base rocks) and the mutual influence of stored mineral substances.
- Based on the factors outlined above, the geological exploration of man-made deposits is also complicated, since it is quite problematic to take samples in the stratum of a bulk lumpy deposit, and the laws of distribution in space of quality characteristics are not always predicted.

Taking into account all the technological complexities of the development of man-made deposits, the percentage of waste should be reduced as much as possible at the stage of its extraction from the subsoil, and the creation of man-made deposits must be carried out in accordance with the principles of their purposeful formation, and not gross waste formation.

At the same time, it is recommended to realize right out of the open-pit of subsidiary minerals extracted, but here the question arises of determining the schedule of mining operations by subsidiary types. Combinatorial optimization problems can be used to control the mode of mining operations in the mining system as a search for the best element in some discrete set. For this purpose, an algorithm for finding the optimal sequence of extraction of geological blocks was developed.

The proposed algorithm is based on the improved method of determining the schedule of mining operations by Arsentiev [28] in accordance with the principles of reducing the current and boundary stripping ratios [29]. According to the proposed algorithm, the input data is loaded first. In the simplest case, the problem can have a set of flat solutions for each unit of the cluster, which consists of quarries, man-made deposits, storages. Therefore, at this stage, a set of transverse or longitudinal sections should be selected, given in the form of a database of blocks, which contain information about their geometric coordinates, as well as the content of each mineral in each block. The next component of the input data is the forecast level of demand for each type of mineral, which must be satisfied by the regional mining cluster. It is usually projected based on long-term contracts and industry prospects.

Next, the main directions of movement of the bottom of the pits are chosen: behind both sides of the pit, along the hanging and lying sides of the deposit, and behind its center. According to the drawn lines of movement of the bottom of the pit, isolines of equal volumes of mining mass are constructed in automatic mode in accordance with the planned ones. Next, there are calculation blocks that intersect with this deepening line and the corresponding extraction cone is calculated, that is, the volume of rocks that must be removed to work this block. After all the cones for all the isolines are calculated, such cones are found that are characterized by minimal deviations of the actual volumes of extraction from the planned ones, and based on their set, the necessary version of the mining operation schedule is chosen.

Despite the organizational and economic difficulties in Ukraine, MPP "Inguletskiy" continues the policy of sustainable development and rational subsoil use. Thus, a large part of the granites extracted in the process of extracting ferruginous quartzites is used for the internal needs of the open-pit: for backfilling and ballasting of open-pit roads, as well as for the construction of the tailings dam.

Today, talc shale also belongs to the overburden rocks of the open-pit, but earlier they were part of the explored Inguletskiy deposit of brick raw material, which was located directly in the contour of the open-pit's mining diversion. Within the boundaries of the Inguletskiy deposit, the layer of talc shale has a sloping bed with an eastern dip. The thickness of the layer in the south of the site is 18 m, in the northern part -64 m, the most characteristic thickness on average -40 m figure 3.

The talc shale occurs according to the rocks of the first shale horizon and belongs to the

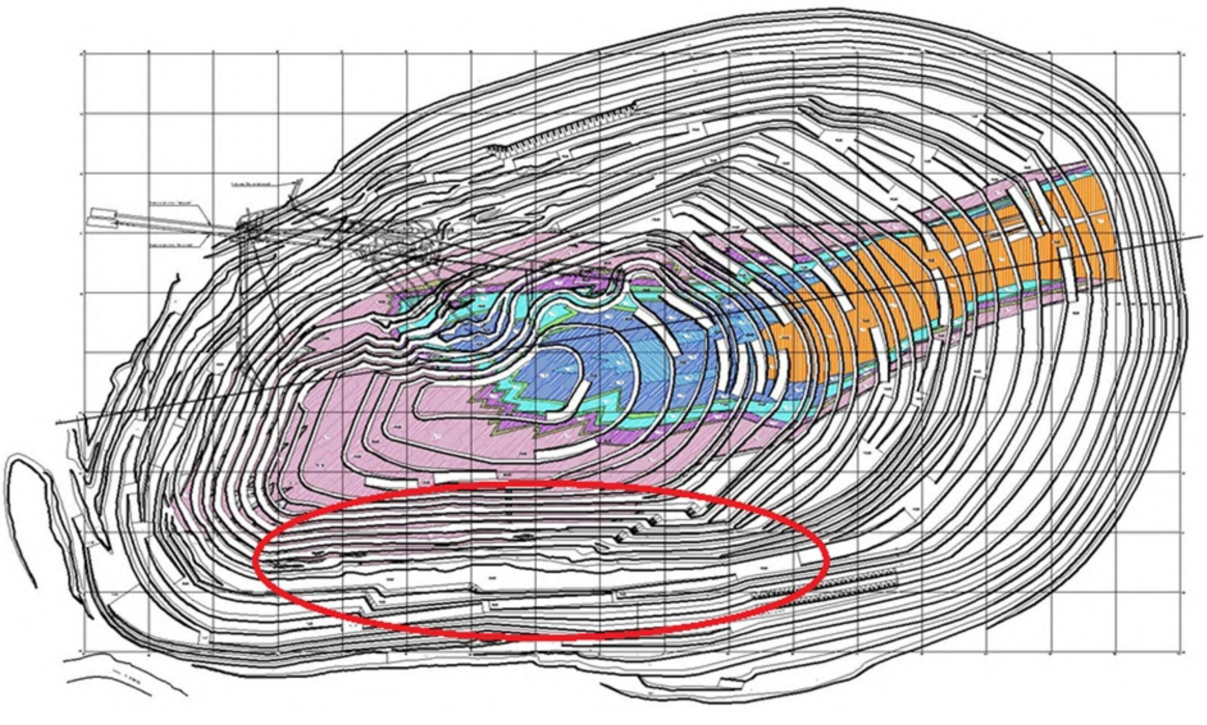

Figure 3. The state of the mining operations of the MPP "Inguletskiy" open-pit for 01.01.2022 with the marked zone of talc shale.

Skelevatska formation, which can be traced in the south of the deposit in the region of the closure of the fold behind the eastern and western wings. The chemical composition of talc shale is given in table 1.

Table 1. Chemical composition of talc shale according to the results of a detailed exploration.

No	Chemical composition	Contents, mass %
1	SiO_2	31.94-48.28
2	Al_2O_3	5.13-15.66
3	Fe_2O_3	0.14-8.43
4	FeO	3.48-13.92
5	MgO	14.28-27.74
6	CaO	0-7.7
7	TiO_2	0.321
8	SO_3	0.11
9	Na_2O	0.1
10	K_2O	0.1
11	others	8.47

According to preliminary estimates of the trust "Ukrgeology", the total reserves of talc shale in the Inguletsk deposit amount to 20-22 million tons with a volumetric weight of 2.6 t/m^3 [30]. Of these, about 200 thousand tons are stored in three sections of a separate part of the waste rock dump, which is a man-made deposit. Areas of storage have a height of 3-3.5 m, the slope angle is 34-38°. The hydrogeological and mining technical conditions allow working out the man-made deposit in an open-pit way. Shales do not require enrichment or processing. Talc shale is planned to be sold in raw form to consumers in Ukraine. MPP "Inguletskiy" plans to conduct their development at the same time in three areas depending on the demand for raw materials.

Considering the low productivity of 20 thousand tons per year, the man-made deposit is expected to be developed in one shift during daylight hours in accordance with the current demand for raw materials. The isolated character of the deposition of man-made raw materials determines the absence of capital and excavation works. To carry out loading work, the use of a CAT-993K loader with a bucket capacity of 10 m^3 or other similar equipment is envisaged. BELAZ-7540B dump trucks with a carrying capacity of 30 tons and BELAZ-7547 with a carrying capacity of 45 tons are accepted as rolling vehicles for internal transport, with further transshipment into railway vehicles.

Thus, the plant intends to ensure the rational use of natural resources, reduce the amount of overburden storage, freeing up space in dumps with an area of 2.68 hectares.

4. Conclusions

The Kryvyi Rih region has all the prerequisites for creating a mining cluster. For this, technological, logistical, economic and financial ties between the "Inguletskiy", "Pivdenniy", "Pivnichniy" and "Centralniy" mining and processing plants and their mineral bases should be strengthened. MPP "Inguletskiy" has significant success in this aspect and can become a driver of such transformations.

Further optimization of the schedule of mining operations within the system of "open-pit-technogenic deposits", and in the future within the mining cluster, will contribute to more complete extraction of subsidiary minerals due to the possibility of meeting demand in a timely manner. In turn, these measures ensure a more complete implementation of sustainable development approaches in the exploitation of mineral deposits by an open-cast method.

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References

[1] United Nation 1992 Rio Declaration on Environment and Development URL https://www.un.org/en/development/desa/population/migration/generalassembly/docs/globalcompact/A_CONF.151_26_Vol.I_Declaration.pdf
[2] United Nation 2012 A /RES/66/288 - Resolution adopted by the General Assembly on 27 July 2012 - The future we want URL https://sdgs.un.org/documents/res66288-resolution-adopted-general-19882
[3] Verkhovna Rada of Ukraine 2011 Pro zatverdzhennya Zahalnoderzhavnoyi prohramy rozvytku mineralno-syrovynnoyi bazy Ukrayiny na period do 2030 roku URL https://zakon.rada.gov.ua/laws/show/3268-17#n14
[4] Vilkul Y, Azarian A and Kolosov V 2013 *Hirnychyy visnyk* **96** 3–10
[5] Peregudov V, Hryhoriev I, Joukov S and Hryhoriev Y 2020 *E3S Web of Conferences* **166** 02004 URL https://doi.org/10.1051/e3sconf/202016602004
[6] Abay A, Imbuga M, Malik C, Singh K and Borodin D 2018 *E3S Web of Conferences* **41** 02010 URL https://doi.org/10.1051/e3sconf/20184102010
[7] Pysmenniy S, Shvager N, Shepel O, Kovbyk K and Dolgikh O 2020 *E3S Web of Conferences* **166** 02006 URL https://doi.org/10.1051/e3sconf/202016602006
[8] Novitasari R, Rosyidi C N and Aisyati A 2021 *IOP Conference Series: Materials Science and Engineering* **1096**(1) 012019 URL https://doi.org/10.1088/1757-899X/1096/1/012019
[9] Chakraborty M K, Ahmad M, Singh R S, Pal D, Bandopadhyay C and Chaulya S K 2002 *Environmental Modelling & Software* **17**(5) 467–480 ISSN 1364-8152 URL https://doi.org/10.1016/S1364-8152(02)00010-5
[10] Hasan S N M S, Kusin F M, Hassim M A and Molahid V L M 2020 *IOP Conference Series: Materials Science and Engineering* **736**(2) 022046 URL https://doi.org/10.1088/1757-899X/736/2/022046
[11] Bolatova A, Kuttybayev A, Kainazarov A, Hryhoriev Y and Lutsenko S 2020 *News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences* **1** 33–38 URL https://doi.org/10.32014/2022.2518-170X.137
[12] Kalinichenko V, Dolgikh O, Dolgikh L and Pysmennyi S 2020 *Mining of Mineral Deposits* **14**(4) 31–39 URL https://doi.org/10.33271/mining14.04.031
[13] Yeremeyev I, Dychko A, Remez N, Kraychuk S and Ostapchuk N 2021 *IOP Conference Series: Earth and Environmental Science* **628**(1) 012014 URL https://doi.org/10.1088/1755-1315/628/1/012014
[14] Vetsner Y, Kazakov V, Doronina V, Avina S, Deineka D, Baturin O and Paleckiene R 2022 *IOP Conference Series: Earth and Environmental Science* **970**(1) 012016 URL https://doi.org/10.1088/1755-1315/970/1/012016
[15] Pysmennyi S, Peremetchyk A, Chukharev S, Fedorenko S, Anastasov D and Tomiczek K 2022 *IOP Conference Series: Earth and Environmental Science* **1049**(1) 012029 URL https://doi.org/10.1088/1755-1315/1049/1/012029
[16] Pysmennyi S, Fedko M, Shvaher N and Chukharev S 2020 *E3S Web of Conferences* **201** 01022 URL https://doi.org/10.1051/e3sconf/202020101022
[17] Rada natsionalnoyi bezpeky i oborony Ukrayiny 2021 Pro stymulyuvannya poshuku, vydobutku ta zbahachennya korysnykh kopalyn, yaki mayut stratehichne znachennya dlya staloho rozvytku ekonomiky ta oboronozdatnosti derzhavy URL https://zakon.rada.gov.ua/laws/show/n0046525-21#Text
[18] Andrusiak N 2019 *Central Ukrainian Scientific Bulletin. Economic Sciences* **35** 53–62 URL https://doi.org/10.32515/2663-1636.2019.2(35).40-52
[19] Antonik V, Babets E, Antonik I and Melnikova I 2022 *IOP Conference Series: Earth and Environmental Science* **1049**(1) 012002 URL https://doi.org/10.1088/1755-1315/1049/1/012002

[20] Antonik V, Shtanko L, Antonik I and Ivachenko V 2022 *IOP Conference Series: Earth and Environmental Science* **1049**(1) 012003 URL https://doi.org/10.1088/1755-1315/1049/1/012003
[21] Batur M and Babii K 2022 *IOP Conference Series: Earth and Environmental Science* **970**(1) 012004 URL https://doi.org/10.1088/1755-1315/970/1/012004
[22] Verkhovna Rada of Ukraine 1994 The Code of Ukraine on Bowels URL https://zakon.rada.gov.ua/laws/show/132/94-%D0%B2%D1%80?lang=en#Text
[23] Verkhovna Rada of Ukraine 1995 Pro zatverdzhennya Poryadku derzhavnoho obliku rodovyshch, zapasiv i proyaviv korysnykh kopalyn URL https://zakon.rada.gov.ua/laws/card/75-95-%D0%BF
[24] Verkhovna Rada of Ukraine 2017 Pro otsinku vplyvu na dovkillya URL https://zakon.rada.gov.ua/laws/show/2059-19#Text
[25] Ivannikov A L, Kongar-Syuryun C, Rybak J and Tyulyaeva Y 2019 *IOP Conference Series: Earth and Environmental Science* **362**(1) 012130 URL https://doi.org/10.1088/1755-1315/362/1/012130
[26] Putranto T W C, Wigati N F S and Pradana H P 2019 *IOP Conference Series: Earth and Environmental Science* **245**(1) 012003 URL https://doi.org/10.1088/1755-1315/245/1/012003
[27] Bochorishvili N, Khomeriki D, Mataradze E, Chikhradze N, Kvavadze S, Robakidze D and Khomeriki S 2021 *IOP Conference Series: Earth and Environmental Science* **906**(1) 012133 URL https://doi.org/10.1088/1755-1315/906/1/012133
[28] Arsentiev A (ed) 1987 *Sovremennyye printsipy teorii proyektirovaniya kar'yerov* (Leningrad: Nauka)
[29] Joukov S, Lutsenko S, Hryhoriev Y, Martyniuk M and Peregudov V 2020 *E3S Web of Conferences* **166** 02005 URL https://doi.org/10.1051/e3sconf/202016602005
[30] Levchuk K 2021 InGOK planiruyet dobyvat' tal'kovyye slantsy iz otkhodov ZhRS URL https://gmk.center/news/ingok-budet-dobyvat-talkovye-slancy-iz-othodov-zhrs

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Development of a method for clusterization of the dissipative structures

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Development of a method for clusterization of the dissipative structures

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Abstract. The dissipative structure (DS) may follow irreversible processes, which occur in the open thermodynamic systems passing and transforming a sufficiently intensive flow of energy. DS can be detected as certain patterns of spontaneous organization in space and time. We consider the DS, which transposes during irreversible ground movement due to landslide or ground pressure manifestation. However, DSs may hide under stochastic noise that impedes their detection. We developed a new method for revealing of DSs in such a stochastic environment using a combination of k-mean clustering, Voronyi tessellation, and the optimal schedule of ground movement monitoring. The developed method has been successfully tested in the case of the irreversible ground movement in the vicinity of a longwall face.

1. Introduction

The majority of processes in the real life are irreversible. According to the modern theory of thermodynamics [1], open systems may spontaneously generate DSs if they pass and transform a sufficiently intensive flow of energy [2]. Investigation of DS promotes a better understanding of the deep mechanism and facilitates more effective control of the complex irreversible processes. In this paper, we consider such processes as landslides [3], sinkholes, and ground movement due to underground mining [4], which expose the environment to the big hazards but effective control of which is far from excellence. A distinctive feature of these processes is that DSs are hidden and it is not easy to reveal them confidently. Traditional approaches propose to describe these processes as definite events allowing their certain parameters [5, 6]. However the modern publications describe the ground movement as a stochastic process [7] and consider its parameters as probabilistic entities [8]. As far as we know, DS has not been revealed during irreversible movement of the ground so far. Recently, DSs were detected for the first time during instrumental observation of a slow landslide development [3] and microseismicity monitoring of the hydrofracturing process [4].

This presentation aims to develop a method that is available to detect DS reliably and unambiguously in processes of ground movement when DS patterns are hidden or veiled under stochastic noise.

2. Interrelation between components of the method

The history of irreversible ground movement depends on the loading path [9]. Therefore, one should monitor the irreversible ground movements as accurately as possible to detect essential features of the irreversible process. Physical modeling is the relevant approach to solve this task considering the trade-off between cost and results. For that reason, we investigated the irreversible ground movement on a physical model constructed of synthetic materials [10].

The height, width, and thickness of the model were 380, 360, and 19 mm correspondingly. We investigated the behavior of an underground opening in the geometric scale of 1:35.8. The synthetic material was made of sand, clay, chalk, and water in proportion 92.26:2.77:1.37:3.6 respectively. The thickness of the rock layers was 2.5–10 mm in the model or 0.089-0.358 m in situ.

The model has been consolidated under the pressure of 89.8 kPa during 15 minutes under vibration with the frequency of 50 cycles and magnitude of 2 mm. The applied pressure was three times as much compared in situ level of the ground pressure. This eliminated possible errors of the ground behavior modeling at the areas where abutment pressure concentrates. The uniaxial compressive strength of the rock was 0.67 MPa in the model or 41 MPa in the real rock mass. Ground pressure was simulated at the top of the model applying the load from 27 to 31 kPa. The movement of the surrounding opening rocks was monitored by a digital camera locating the position of special marks, whereby the standard deviation of the displacement measurement was 0.39 mm or 2.5 pixels on the digital frames. A confidence interval of four, five, and six pixels corresponded to 90.7%, 95.6%, and 99% reliability of the displacement measurement.

The trajectories of the three marks during model testing are demonstrate in figure 1.

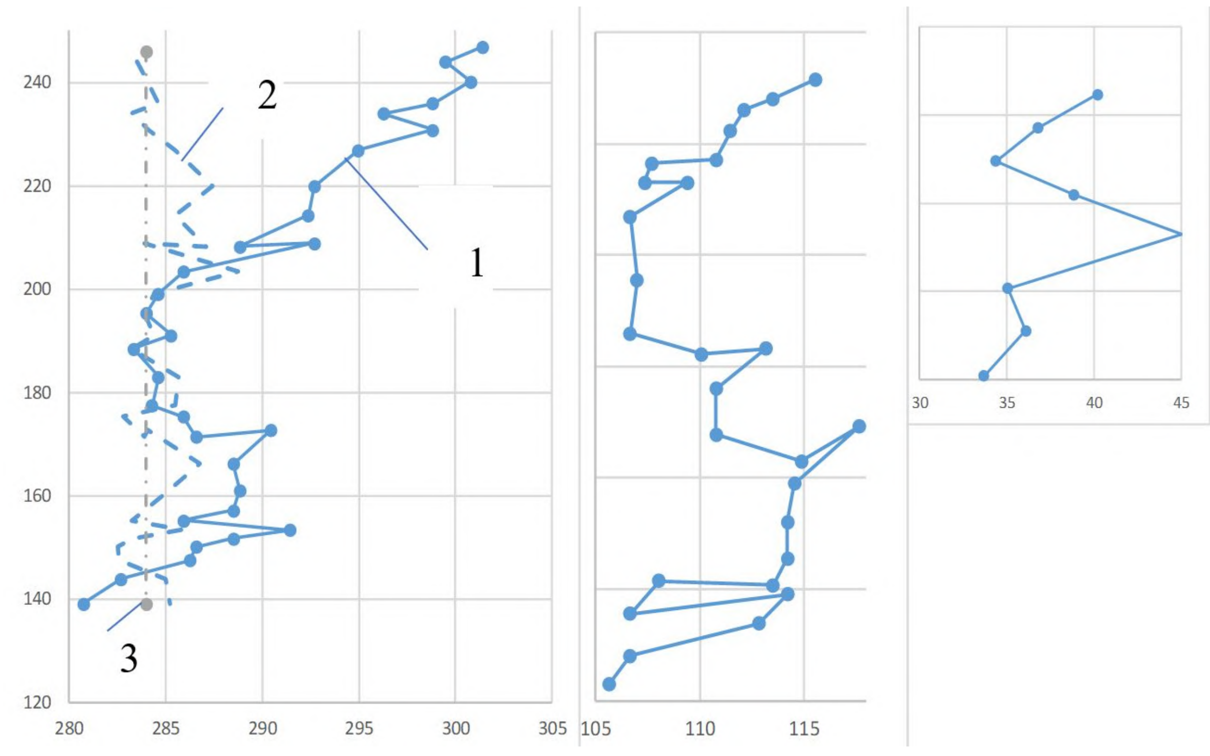

Figure 1. Trajectory of the selected marks.

The marks' coordinates are indicated in pixels. Ten millimeters in the digital picture corresponded to 12 pixels. A separate section of a trajectory reflects a path of the mark between consecutive pictures, which were made on the basis of the constant time interval. We characterize these elementary paths as incremental displacements. It may be seen that the marks change both directions of movement and velocity.

It is important to emphasize the stochastic nature of the displacements although the general tendency of the movement was down to the opening since the marks were selected in its roof. At the same time, one may notice the transversal movements of the marks, which are impossible to disregard. The transversal deviation of the marks is significant and their neglection may cause loss of important information that may be crucial for DS detection.

In the left fragment of figure 1, position 1 indicates the trajectory of the first mark, intermitted line 2 presents the magnitudes of the incremental displacements, and vertical line 3 limits of 90.7% confidence interval. Comparison of lines 2 and 3 shows that less than 10% of the measurements were made with insufficient confidence. However, an increase in the confidence interval simplifies the trajectory and many essential features of the trajectory might be lost. The more interval between successive sessions of monitoring the less valuable information remains. Frequently, researchers monitor the initial and the final state of a landslide that completely deprives any possibility to reveal DS [11, 12] (see the intermitted arrow in figure 2,c).

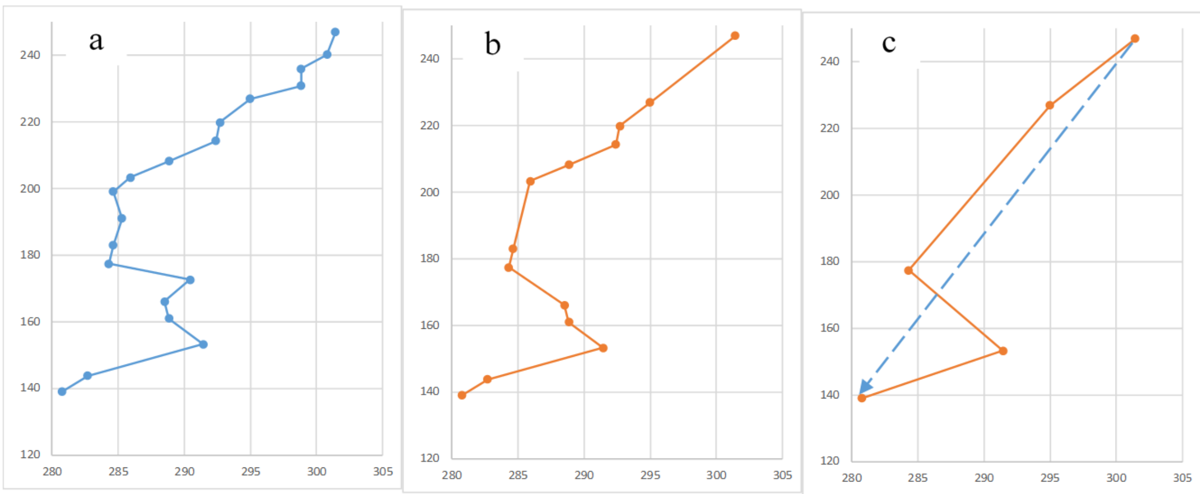

Figure 2. Trajectory of the same mark: a, b, c – 90.7; 95.6; 99% confidence interval.

That is why revealing DS in the ground movement process needs a special approach. First the most informative is the irreversible ground movement because it complies with the thermodynamics of irreversible processes [13]. According to Glansdorff et al [13], an open thermodynamic system strives to minimize the production of entropy if it is not far from equilibrium. The entropy is calculated as the production of thermodynamic forces and flows. Ground pressure and gravity stand for the thermodynamic forces and irreversible ground displacements for the thermodynamic flows.

Second, it is crucial to minimize the error of ground displacement measurements to reveal DS as a fine natural structure, which may hide in the stochastic noise. Evidently, the probability of DS detection is reversely proportional to the error of measurement.

Third, the periods of sequential monitoring sessions should be minimized and complied with the errors of measurements. There is an optimal period that maximizes the probability of DS revealing: a very short interval between sequential measurements increases the cost of monitoring whereas expansion of this period increases the probability that DS will be lost or mixed with other DS.

Finally, the density of the marks or monuments (in situ) in space should be optimized to prevent losses of the valuable information on one hand and to minimize the cost of the monitoring

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on the other. The distance between adjacent monuments should be commensurate with the average dimension of the blocks comprising the ground body: shorter distance increases the cost of the detection but the oversized arrangement may cause to lose DS. As the first approximation, the distance between adjacent monuments should be in a range from 2 to 10 of the block's dimension. All the aforementioned conditions should be satisfied to develop a reliable method of DS detection.

3. Development of the method

We used a powerful method of variogram analysis [14] and k-means clustering [15]. The variogram is a statistical second-order moment that is widely used during simulation and analysis of spatial correlation. The variogram $2\gamma(x, x+h)$ for the value of a spatial variable $Z(x)$ at the two points x and $x+h$, which a separated by a vector h, is expressed by variation of the variable difference in the abovementioned points:

$$2\gamma(x, x+h) = E[|(Z(x) - \mu(x)) - (Z(x+h) - \mu(x+h))|2]. \tag{1}$$

where μ denotes an expected value.

Method k-means has been used for simultaneous variance minimization of distances between vectors within a cluster and maximizing of the distance variance between the clusters' centers. The distance between the vectors is determined in Euclid space that has arbitrary dimensions. Importantly, the task of classification of the random variables, and particularly for the detection of DS on a vector mosaic of the incremental displacements of the ground or the rock mass, has no single-entry solution. That is why the possible number of the clusters was first set equal to two and then increased until a certain condition has been satisfied. We controlled the classification process by the variance dynamics of the distances from the clusters' centers to the common center. Notably, we used interpolated field of the ground displacements to calculate the variogram, whereas only factual changes of the monuments' coordinates were involved for the cluster analysis.

The results of calculating the distances between clusters in Euclidean space at the stage when there were seven clusters are shown in the table 1. As the number of clusters increased, the length and orientation of the vectors changed as may be seen in figure 3. Some vectors demonstrated certain stability whereas the other disintegrated to the components. Essential variability of the vectors took place at the initial stages of clusterization.

Thus the only vector marked by a triangle remained almost unchanged when the number of the vectors increased from five to seven. The other vectors changed their length and/or orientation. The process of stabilization of the distances' variances occurs both between the vectors in every cluster and among the clusters as is illustrated in figure 4. The distance variance

Table 1. Distance between clusters.

Number of cluster	1	2	3	4	5	6	7
1	0.0						
2	51.2	0.0					
3	86.0	54.6	0.0				
4	43.8	54.7	54.6	0.0			
5	56.8	55.4	109.8	91.8	0.0		
6	91.8	40.9	50.7	83.9	85.7	0.0	
7	89.4	48.2	90.5	102.8	55.1	45.8	0.0

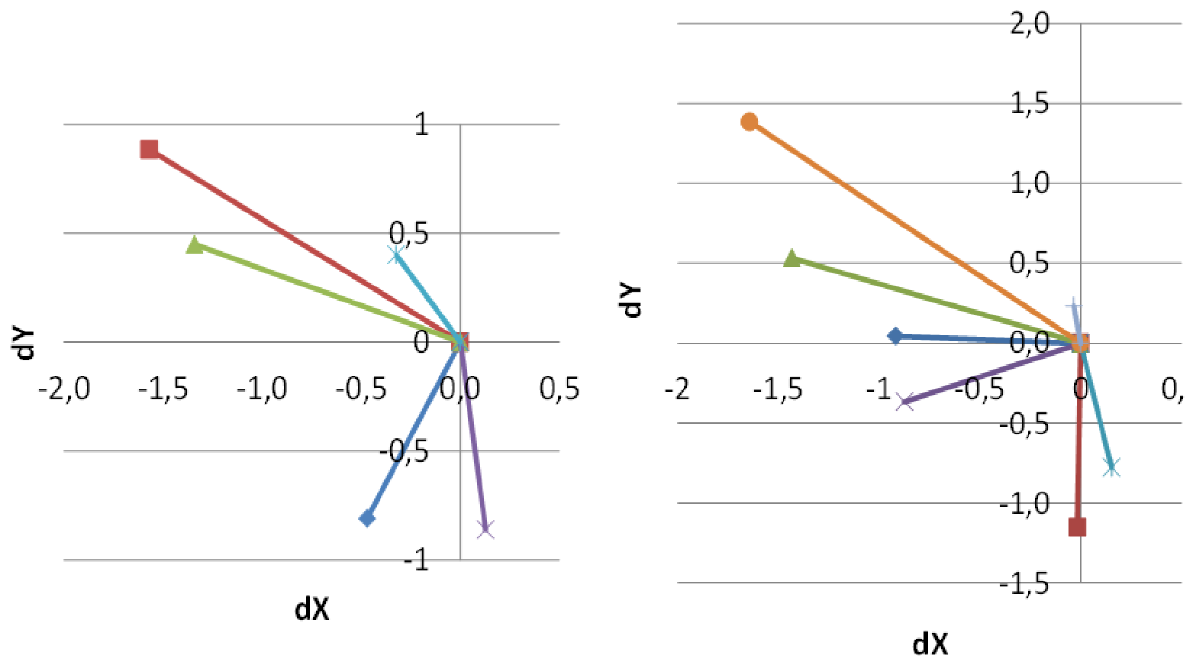

Figure 3. Evolution of the cluster parameters due to increasing of their number.

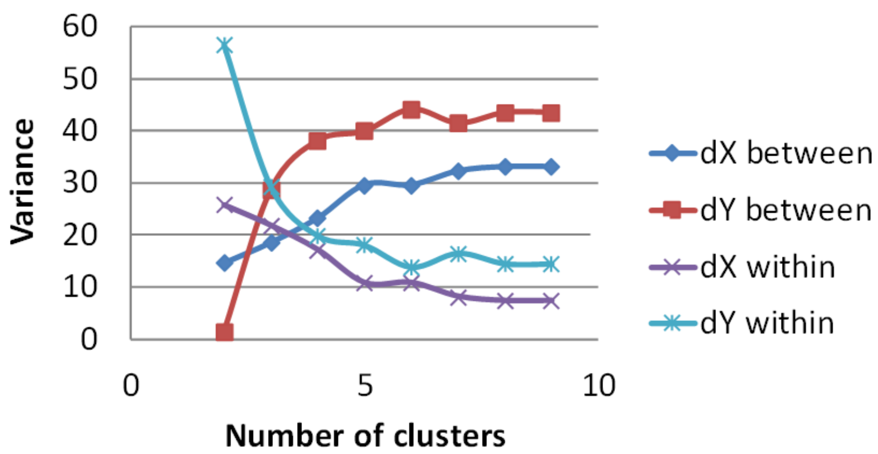

Figure 4. Illustration of the variance stabilization.

is shown separately along the X and Y-axis. Importantly, clusterization of the vectors was made according to their components separately.

As it can be seen the stabilization of the variances occurs for both components of the vectors after the number of the clusters increased to nine. Nonetheless, further prolongation of the clustering has shown that the k-means algorithm finds a more fine difference between clusters as the number of clusters grows. Evidently, the algorithms will start to classify the vector mosaic according to the signs, which have not physical but stochastic nature. Therefore, an auxiliary criterion is needed to determine the moment when the clusterization process should be terminated.

According to thermodynamics, the most probable state of ground corresponds to the maximum of its entropy [13]. This state can be expressed by the Boltzmann-Shannon formula:

$$S_i = -k \sum p_j ln p_j, \ 1 \leq j \leq N. \tag{2}$$

where S_i is entropy, p_j is the probability that j-th cluster will emerge, k is a constant, N is the total number of clusters.

The entropy S_i reaches the maximum when probabilities of all clusters will be equal, namely:

$$p_j = \frac{1}{N}. \tag{3}$$

In this case the entropy production $\frac{dS_i}{dt} = 0$.

In this situation, the results of monitoring have a certain error, and condition (3) is impossible to reach. Nevertheless, this condition is a threshold to which cluster probabilities may be reduced. In order to do this, we counted the number of cases when the same cluster occurred due to the increase of the clusters' number in the limits of measurement error.

Then we calculated the entropy according to formula (3) and reduced it to S_i. Tests demonstrated that it is possible to fix the moment when the entropy reaches the extremum and this is expedient to terminate the clustering process.

Another problem concerns the determination of the cluster boundaries. The practice has shown that adjacent clusters overlap and this introduces uncertainty. To solve this problem, we used Voronyi tessellation [16] that determines a crisp boundary between adjacent clusters as the lines, which are normal to the lines joining the clusters' centers. These locations of the boundaries correspond to condition (3) that minimizes the error of measurement of the monuments' position.

4. Testing of the method: a case study

We tested the developed model on a case of rock mass subsidence in the vicinity moving longwall face. A base friction modeling has been used to imitate the ground displacement due to a coal seam extraction.

Rock mass was modeled with discrete elements, which have been stacked on a desk within a rectangular frame. The gravity was simulated by the traction of the frame along the deck. We regulated the rate of the longwall movement by the incremental step of its advance along the coal seam. The more the step was between serial pictures the more the rate of the longwall advance.

At the first glance, the appearance of the model on both pictures in figure 5 is identical. However, the incremental displacements are essentially different.

The incremental displacements of the marks in the moments when the longwall was replaced from positions 5852 to 5853 and 5853 to 5854 respectively demonstrate figure 6, figure 7. The displacements, which are confined within the boundaries were registered with 90% reliability. The overlay of the vector displacements and Voronyi tessellation are depicted in figure 7.

Meaningful clusters of DS are marked with numbers from 1 to 6. The distances between clusters were calculated according to both orientations of the displacement vectors and their magnitudes (table 2). Seemingly, some clusters may contain different vectors (figure 7).

However, k-means method ensures that the difference among the vectors within a cluster will be minimal according to all their parameters. Analysis has shown that the developed method is efficient because the classification grasps the physical meaning of the irreversible process of the ground movement. For instance, clusters 1 and 2 are found beyond the zone of active movement. These clusters moved to the gob or zone of the smooth sagging where the ground pressure was on the way to its recovery. Displacement vectors of cluster 2 turned to the longwall advance direction whereas cluster 1 oriented downward and slightly to the gob. Cluster 4 is located at

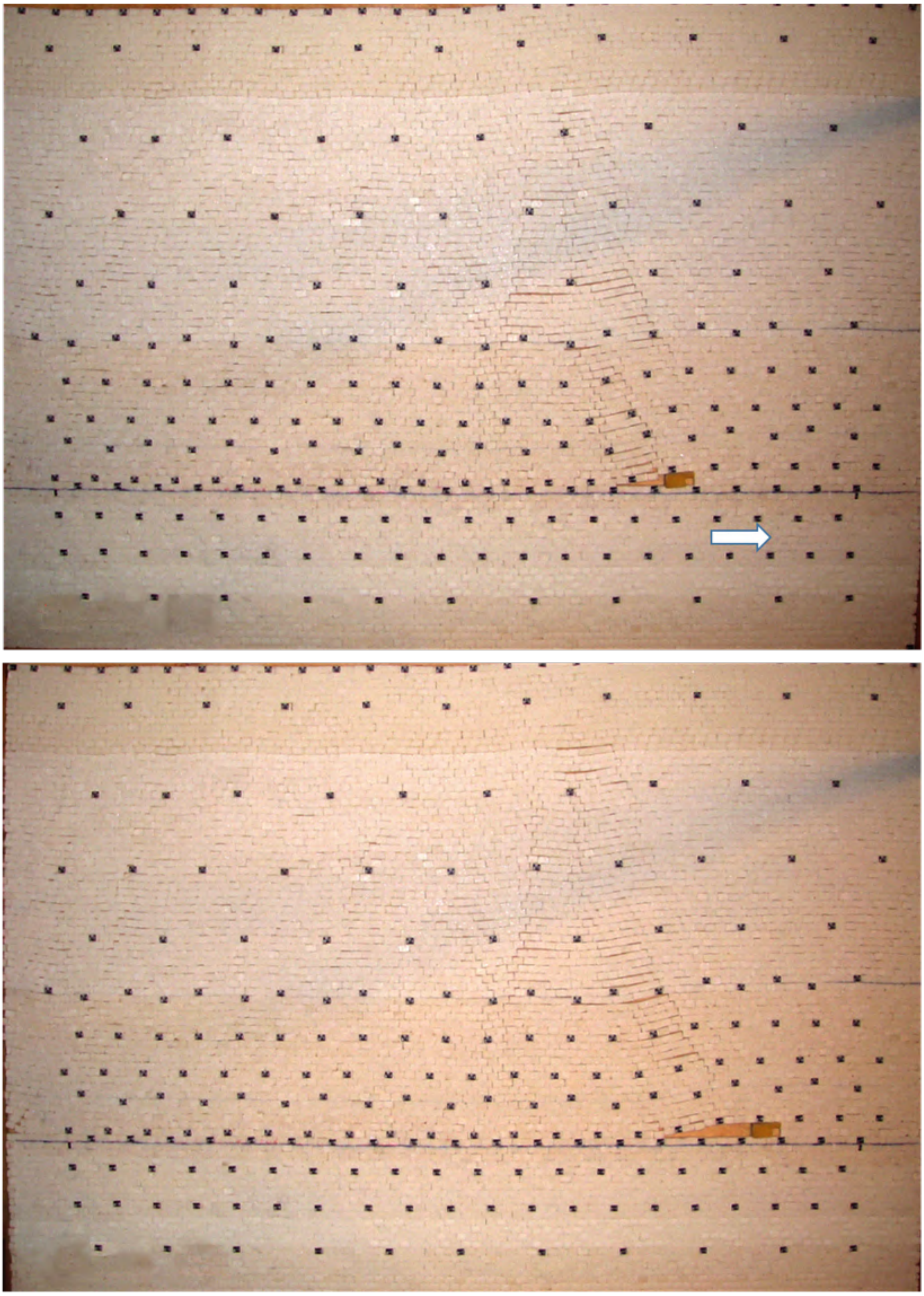

Figure 5. Digital pictures of successive positions of the longwall.

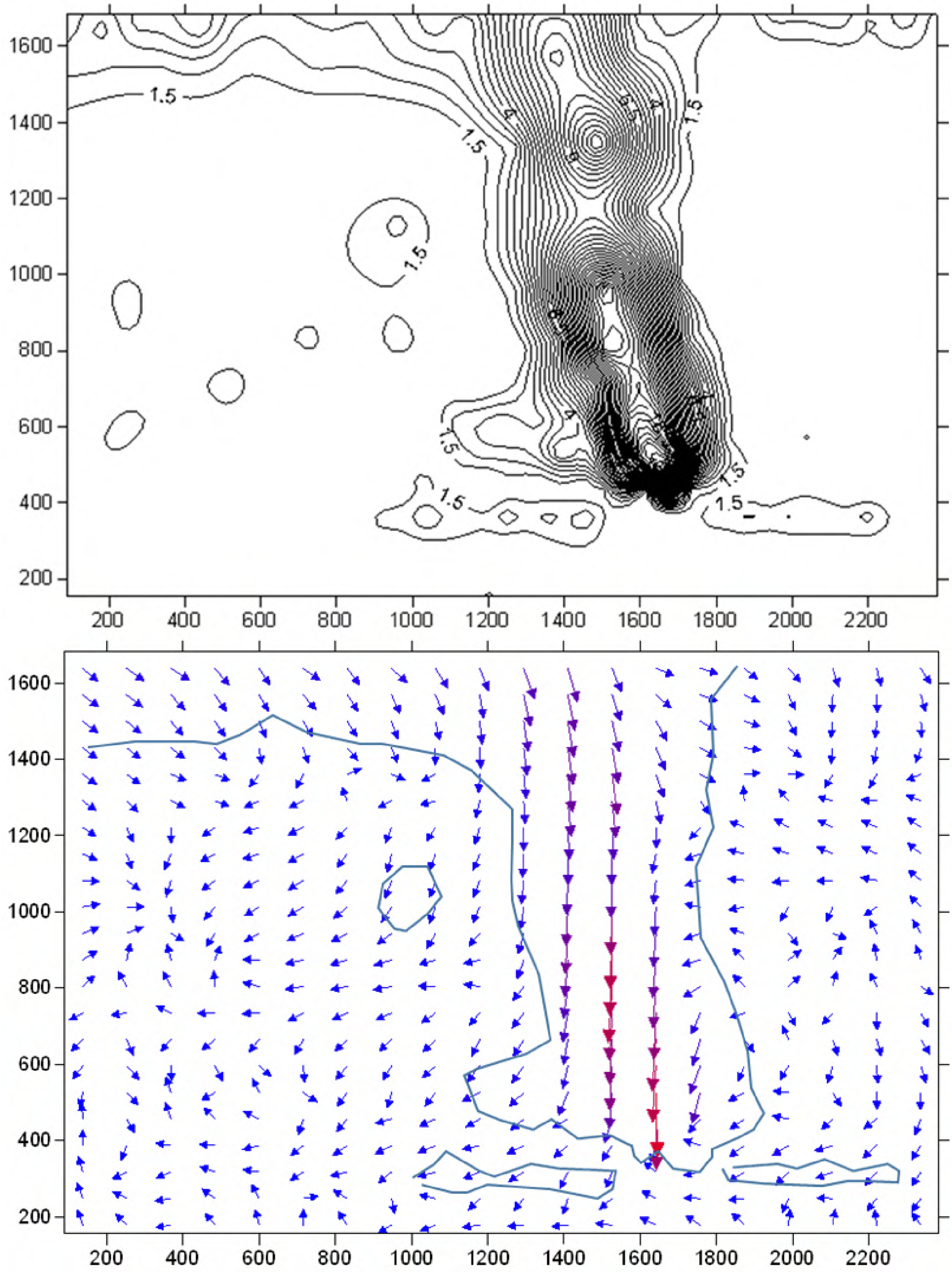

Figure 6. Incremental displacements of the rock mass between positions 5852 and 5853.

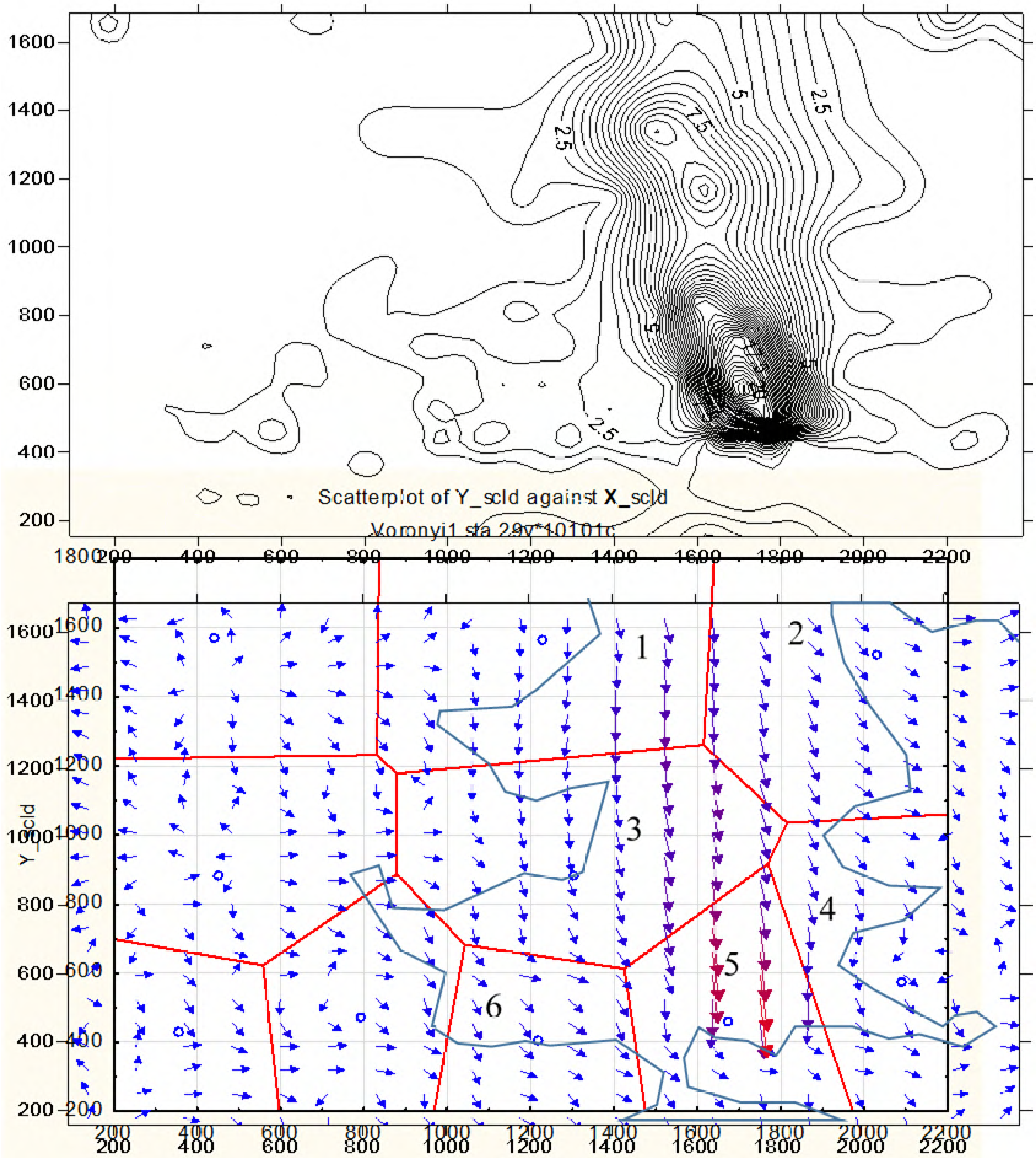

Figure 7. Overlay of incremental displacements of the rock mass between positions 5853 and 5854 and Voronyi mosaic.

the rib of the coal seam in the so-called abutment pressure zone. Cluster 5 encompassed the zone where the most active subsidence occurred over the longwall void. Clusters 3 and 6 shifted to the gob where the caved rocks consolidate, although the displacement vectors of cluster 6 have an apparently bigger component in the direction of the longwall advance. Therefore the developed method of clusterization facilitated the revealing of DS localizing not only the cluster boundaries but accounted for the physical meaning of the irreversible processes that follow the

Table 2. Distance between meaningful clusters.

Number of cluster	1	2	3	4	5	6
1	0.0					
2	484	0.0				
3	560	281	0.0			
4	475	421	214	0.0		
5	691	242	231	444	0.0	
6	812	329	442	651	216	0.0

ground movement.

Let us pay attention to the position of the immediate roof that was at the distance of 4 m from the longwall face or at the rear part of the powered support canopy when the face was in the previous position (5852). However, this roof kept still hanging after the next step advance of the longwall to the distance of 4 m. It would seem the incremental displacements of the rock mass may be neglected, although DS can evolve essentially even for such a short period.

The dramatic difference between the displacement distribution is that all vectors are oriented downward and to the left or the gob in figure 6 whereas they turned to the right of the face at the next step increased by only 4 m. In addition, the area of the rock mass expanded where the incremental displacements were detected with the confidence of more than 90%. Such a difference is not random and may be explained from a physical point of view.

The maximal incremental displacements occur in the zone of maximum sag and possible delamination of the rock layers. The pictures in figure 5 and distributions in figure 6 highlight this zone that is inclined to the horizon under the angle of 700. This complies with a common vision of the subsidence mechanism. The strata caves as cantilever beams, which disconnect from the solid rock mass on one hand and rotate in figure 5 clockwise on the other. This rotation brings closer the rear end of the cantilever beams to the longwall face. These two opposite incremental movements prevailed by turn, in successive order: at the stage 5852-5853 the disconnection component moved the undermined strata to the left or the gob while the strata shifted to the right at the next step 5853-5854. Such maneuvers become possible due to DS evolution and our method allowed distinguishing this fine behavior of the rock mass. Let us stress that almost all displacement vectors abruptly turned from the left to the right dramatically changing the pattern of DS.

Based on [13] it may be suggested that such a sharp replacing of the DS pattern might be caused by a small fluctuation of the ground pressure. Some displacement vectors change their orientation to 10 pixels exceeding the error of measurements by order.

5. Conclusion

The ground movement is a typical irreversible process that exposes the environment to hazards during landslides, sinkholes, hydrofracturing, and other dangerous and poorly predicted events. According to thermodynamics, such irreversible processes may be followed by DS, which can be used to control the ground effectively. However, DSs are difficult to detect and identify because of the stochastic nature of the irreversible ground movement.

We have formulated several conditions that should be satisfied to develop a reliable method of DS detection. First the most informative is the irreversible ground displacements because they comply with the thermodynamics of irreversible processes. The irreversible displacements represent the thermodynamic flows, which generate the entropy acting together with the thermodynamic forces that are expressed as the ground pressure. Second, it is crucial to minimize the error of ground displacement measurements to reveal DS as a fine natural structure, which may hide in the stochastic noise. Third, the periods of sequential monitoring sessions should be minimized and complied with the errors of measurements. There is an optimal period that maximizes the probability of DS revealing: a very short interval between sequential measurements increases the cost of monitoring whereas expansion of this period increases the probability that DS will be lost or mixed with other DS. Finally, the density of the marks or monuments in space should be optimized to prevent losses of the valuable information on one hand and to minimize the cost of the monitoring on the other. The distance between adjacent monuments should be in a range from 2 to 10 of the rock mass block's dimension.

We used the variogram algorithm and K-means method of clustering to detect DS. The number of the clusters was assigned starting from two and sequentially increased until the minimum distance variance between the displacement vectors within the clusters and maximum of the variance between clusters stabilize. We proposed an auxiliary criterion for termination of the clustering process as the minimum entropy production.

The developed method of DS clustering has been tested successfully in the case of the irreversible ground displacement around moving longwall face. The new method not only revealed specific patterns of the DS but complied with the physical sense of the irreversible ground movement.

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References

[1] Prigogine I and Lefever R 1973 Theory of Dissipative Structures *Synergetics: Cooperative Phenomena in Multi-Component Systems* ed Haken H (Wiesbaden: Vieweg+Teubner Verlag) pp 124–135 ISBN 978-3-663-01511-6 URL https://doi.org/10.1007/978-3-663-01511-6_10
[2] Kondepudi D and Prigogine I 2014 *Modern Thermodynamics: From Heat Engines to Dissipative Structures* (Wiley) ISBN 9781118371817 URL https://doi.org/10.1002/9781118698723
[3] Nazimko V and Zakharova L 2017 *Acta Geodynamica et Geomaterialia* **14**(4) 445–462 ISSN 12149705 URL https://doi.org/10.13168/AGG.2017.0025
[4] Nazimko V V, Zacharova L M and Pidgurna O U 2021 *Arabian Journal of Geosciences* **14** 1540 ISSN 1866-7538 URL https://doi.org/10.1007/s12517-021-07493-6
[5] Fleming R W and Varnes D J 1991 Slope movements *The Heritage of Engineering Geology; The First Hundred Years* (Geological Society of America) ISBN 9780813754154 URL https://doi.org/10.1130/DNAG-CENT-v3.201
[6] Gambolati G and Teatini P 2015 *Water Resources Research* **51**(6) 3922–3955 ISSN 00431397 URL https://doi.org/10.1002/2014WR016841
[7] Peng S S (ed) 2020 *Surface Subsidence Engineering: Theory and Practice* (CSIRO Publishing)
[8] Glass C E 2013 Chapter 8 - Dangers from Ground Subsidence *Interpreting Aerial Photographs to Identify Natural Hazards* ed Glass C E (Oxford: Elsevier) pp 123–131 ISBN 978-0-12-420018-0 URL https://doi.org/10.1016/B978-0-12-420018-0.00008-7
[9] Giorgetti C and Violay M 2021 *Geophysical Research Letters* **48**(8) e2020GL091466 ISSN 0094-8276 URL https://doi.org/10.1029/2020GL091466
[10] Mei C, Fang Q, Luo H, Yin J and Fu X 2017 *Advances in Materials Science and Engineering* **2017** 1–8 ISSN 1687-8434 URL https://doi.org/10.1155/2017/1565438

[11] Szafarczyk A 2016 *Acta Geodynamica et Geomaterialia* **13**(2) 213–222 ISSN 12149705 URL https://doi.org/10.13168/AGG.2016.0003
[12] Amitrano D, Gaffet S, Malet J P and Maquaire O 2007 *Bulletin de la Société Géologique de France* **178**(2) 149–157 ISSN 1777-5817 URL https://doi.org/10.2113/gssgfbull.178.2.149
[13] Glansdorff P, Prigogine I and Hill R N 1973 *American Journal of Physics* **41**(1) 147–148 ISSN 0002-9505 URL https://doi.org/10.1119/1.1987158
[14] González S, García S, Li S T and Herrera F 2019 *Information Sciences* **474** 187–204 ISSN 00200255 URL https://doi.org/10.1016/j.ins.2018.09.062
[15] Rodrigues E, Torok L, Liatsis P, Viterbo J and Conci A 2017 *Pattern Recognition* **66** 392–403 ISSN 00313203 URL https://doi.org/10.1016/j.patcog.2016.12.027
[16] Voronoi G 1908 *Journal für die reine und angewandte Mathematik (Crelles Journal)* **1908**(133) 97–102 ISSN 0075-4102 URL https://doi.org/10.1515/crll.1908.133.97

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Numerical simulation of the surface subsidence evolution caused by the flooding of the longwall goaf during excavation of thin coal seams

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Abstract. Underground mining has a significant influence on ground movement, which induces serious environmental disturbances on land. Movements of the rock strata can be the cause of changes in the hydrogeological regimes of groundwater. As a result, the risk of flooding of the longwalls goaf increases. The specific phenomenon of the Ukrainian Donbas is the flooding of the underground roadway system at the result of the closure of the mines. Water saturation of rocks leads to a decrease in its strength. The result is repeated subsidence. The activation of the ground movement processes over the longwall goaf due to their flooding has not been studied enough. In this paper, for the geological conditions of thin coal seams typical for the Ukrainian Donbas, ground movement evolution caused by flooding of longwalls goaf was studied. Ansys code was used to analyze the evolution of surface displacement in different hydrogeological conditions. As a result of numerical simulation, it was found that full flooding of the longwall goaf leads to an increase in surface subsidence by 22.4%, while the length of the trough increase by 1.3%. Maximal inclination increases by 34.4%, and maximal curvature – by 74%. This contributes to a significant increase in hazards for surface infrastructure located on the edges of the subsidence trough. The control of the negative impact on surface infrastructure objects, water and agro-industrial objects can be ensured by a timely prediction of ground movement and the implementation of surface controlling methods to prevent critical surface deformations.

1. Introduction

The underground mining causes a failure of the equilibrium state in the rock strata, provokes irreversible deformations and movements of rocks in the undermining zone. Underground mining has a significant influence on ground movement (also known as subsidence), which induces serious environmental disturbances on land [1]. These phenomena have a negative impact on surface infrastructure objects, water and agro-industrial objects, specific objects mining companies such as waste rock dump [2].

In fact, back to the early days of the 1960s, the processes of ground movement and deformations in the zones of longwall undermining had been studied. The study of the subsidence phenomena and its negative impact on surface is carried out by the following methods:

- by field monitoring [3–6];

- by physical similar simulation [7–9];
- by numerical modeling [10–20].

Zhang et al. [3] presented a study of field measurement and numerical simulation on mining-induced subsidence in an area of Northwestern China. The panels with dimensions 241 m wide and over 3000 m long were extracted. It was showed that surface subsidence lags far behind panel extraction; the subsidence influence through the whole length of a longwall panel varies.

Guney and Gul [4] described and discussed the evaluating of the influence of subsidence on irrigation pipeline structure based on the field data using surface deformation prediction system software.

Zhao et al. [5] reported an analysis result of the eld investigation of the ground ssures and the establishment of GPS monitoring network. The ground deformation and damage has been monitored and researched for the 10 years. The maximal vertical displacement reached 1,720 mm and accompanied by the rapid development of ground ssures.

Nazarenko and Stelmaschuk [6] developed a spatio-temporal model of the formation of a displacement trough for the conditions of coal mines in Western Donbas based on the results of field instrumental monitoring. A new type of isolines is proposed - chronoisosediments, which characterizing the time and place of occurrence of subsidences.

Zhou and Yu [7] presented results of the physical simulation experiment. Based on the microseismic energy distribution cloud chart, the area of water-conducting fracture zone was divided. After fully mining, the overburden caving height was stable, and the height development range of the water-conducting fracture zone was 100120 m, which is consistent with the height of the overburden caving envelope.

Yanli et al. [8] studied the movements of rocks of the upper layers, which were provoked by mining operations, analyzed the regularities of the evolution of cracks using the methods of measurement and physical modeling.

Stupnik et al. [9] proposed a method to determine quantitative composition of the equivalent material for the study the rock mass stability in the laboratory conditions.

In world practice, the software package Surface Deformation Prediction System (SDPS) has gained wide popularity [10–12]. Based on empirical or site-specific regional parameters, the model quantifies a variety of ground deformation indices for both longwall and high extraction room-and-pillar mines [13].

However, since SDPS is based on statistical analysis, it does not provide an opportunity to investigate the mechanism of activation of subsidence in non typical geological conditions, for example during the flooding of mine roadway system.

Methods of numerical modeling have not these shortcomings. Various software systems are based on the finite difference method (FDM), (FLAC3D) [14, 15], finite element method (ANSYS) [16–20], method of discrete elements [21].

Jeromel et al. [14] presented results of the numerical simulations of sub-level coal mining by FLAC3D. The simulation results are comparable with the values obtained by the in-situ measurements during coal excavation in the Velenje Coal Mine.

Zhao et al [15] presented a case study on predicting the distribution of the ground ssures and water-conducted ssures induced by the coal mining. The analysis of the calculated by FLAC3D movement and deformation of ground surface and strata allowed to predict the distribution of ground ssures and water-conducted ssures.

A finite element analysis was performed by Marian et al [16] to study the state of stresses on the structures of buildings subjected to the impact of underground mining of hard coal seams in the Jiu Valley Basin.

The prediction of subsidence by the finite element method was in the center of attention of scientists of UkrNDMI. For example, Sakhno et al [17] presented the simulation results of ground movement and deformations, which is based on a numerical nonlinear solution by ANSYS. An example of the calculation of displacements for the conditions of the mine "Krasnolymanska" was given. Grishenkov and Golubev [18] presented the results of the numerical simulation of water inflow in mine roadway to the activation of subsidence over a single longwall. ANSYS code is widely used to analyze the stability of rock outcrops [19, 20].

Zhang et al. [21] proposed a locally adaptive remeshing method for FDM modeling of largely deformed surface subsidence induced by underground mining. The effectiveness of the proposed method has been veried by comparing the surface deformation for the Yanqianshan iron mine.

This analysis shows that modeling by numerical methods allows to visualize the process of deformation of rock and the surface and obtain sufficient accuracy of the modeling results.

The basic regularities of the subsidence are sufficiently well-studied and they are the basis of relevant normative documents that take into account regional character. For the conditions of the Ukrainian Donbas, the parameters of the subsidence trough are calculated in accordance with the DSTU 101.00159226.001-2003 "Rules of undermining Earth surface objects" [22]. This makes it possible to predict subsidence in conditions of homogeneous rock with sufficient accuracy.

However, geomechanical processes can differ significantly from idealized ones due to the presence of systems of geological fissures, rock heterogeneity, hydrogeological processes, etc. These special situations are the subject of research of scientists.

Movements of the rock strata can be the cause of changes in the hydrogeological regimes of underground and groundwater. As a result, the risk of flooding of the longwalls goaf increases.

Another phenomenon that is specific for the coal mines of the Ukrainian Donbas is the flooding of the underground roadway at the result of the closure of the mines and the increase in the mine water level. The risk of increased water inflows into roadways system due to mining stoppages caused by military operations is increasing. Flooding causes changes in the physical and mechanical properties of rock mass, provokes the development of deformation processes in the rock strata, and deepens the negative consequences of undermining.

The intensity of flooding and the geometry of flooded zones are determined by technological factors that depend primarily on the technology of longwall mining. Cavities and open cracks are the main ways of underground water transit.

Nowadays, scientists are paying more attention to the impact of undermining on groundwater system and on surface water objects. For example, Booth et al. [23] discussed the impact of mining on groundwater including decline and recovery of water levels. Dawkins [24] discussed potential management and rehabilitation requirements of environmental effects from longwall subsidence on streams, lakes, and groundwater systems.

However, the activation of the ground movement processes over the longwall due to their flooding has not been studied enough. Water saturation of rocks leads to a disturbance of the equilibrium in the rock stratum and to the destruction of previously formed equilibrium vaults, as a result of a decrease in the strength of the rocks. The deformation characteristics of the rocks are also changing. The result is repeated subsidence.

These phenomena show the importance of timely prediction of subsidence and the development of methods for the protection of surface infrastructure objects due to the flooding of the roadways system of coal mines.

In this paper, for the geological conditions of thin coal seams typical for the Ukrainian Donbas, through numerical simulation ground movement evolution at the result of flooding of longwalls goaf was studied. This study provides a characteristic on the influence of mine water rising level of longwalls goaf on the activation of subsidence.

2. Characteristics of the study area

The case study mine is located in the west-southern part of Pokrovsk region, Donbas, Ukraine.

The Selidove city is located near the western border of the mine field. The villages of Novomykolaivka, Mykhailivka and Kotlyarevka are located within the boundaries of the mine field and near it. Mykhailivka and Marynivka villages are located in the undermining zone.

The average annual water inflow is 500 m^3/year. The rock strata above the southern part of the mine field, namely 1 and 2 the southern longwall the l1 seam, are the objects of the study.

The average thickness of the coal seam in the studied area was 1.05 m, the dip angle varied from 11 to 13 degrees. The research area included two longwall goafs. The depth of the ventilation roadway of the 1th southern longwall of the l1 seam is 376 m; the depth of the conveyor roadway of the 1th southern longwall of the l1 seam is 476 m.

The Donetsk-Novogrodivka highway, Donetsk-Selydove highway and Mykhailivka village located on the undermining surface. The part of the mine plan with surface objects is shown in figure 1.

The highway Donetsk-Selidove is in the undermining zone of southern longwalls. At the same time, the highway located almost perpendicular to the seam strike line. This line is marked as a section line (figure 1) for a numerical simulation.

3. Methods

We used method of numerical simulation and method of engineering and graphic analysis to investigate surface subsidence in undermining zone.

During the analytical analysis of ground movement elements on land, calculations and graphic constructions were carried out, in accordance with the recommendation of normative document DSTU 101.00159226.001-2003 [22].

Traditional ideas about overburden deformation zones caused by longwall subsidence were accepted. The height of the caved zone was taken equal to 8 times the thickness of the seam. The height of the fractured zone was 60% of the length of the longwall, which corresponds to generally accepted ideas [25–27].

Mine water level rise and goaf flooding were modeled in two stages. At the first stage, the height of the flood level was 40% of the height of the fractured zone, at the second stage – 100% of the height of the fractured zone. Schemes of deformation zones caused by longwall subsidence and subsequent flooding are shown in figure 2.

Finite element analysis software system Ansys was used. The modeling was carried out in a volume setting on a natural scale. Due to the obvious symmetry of the model with respect to the length of the panel, the thickness of the model was assumed to be much smaller than its other dimensions and was 10 m. The sidewalls of the model were fixed from the corresponding normal displacement, the bottom boundaries – from vertical displacement. The model was loaded by gravitational forces. The Drucker-Prager model was used to simulate the behavior of rock mass.

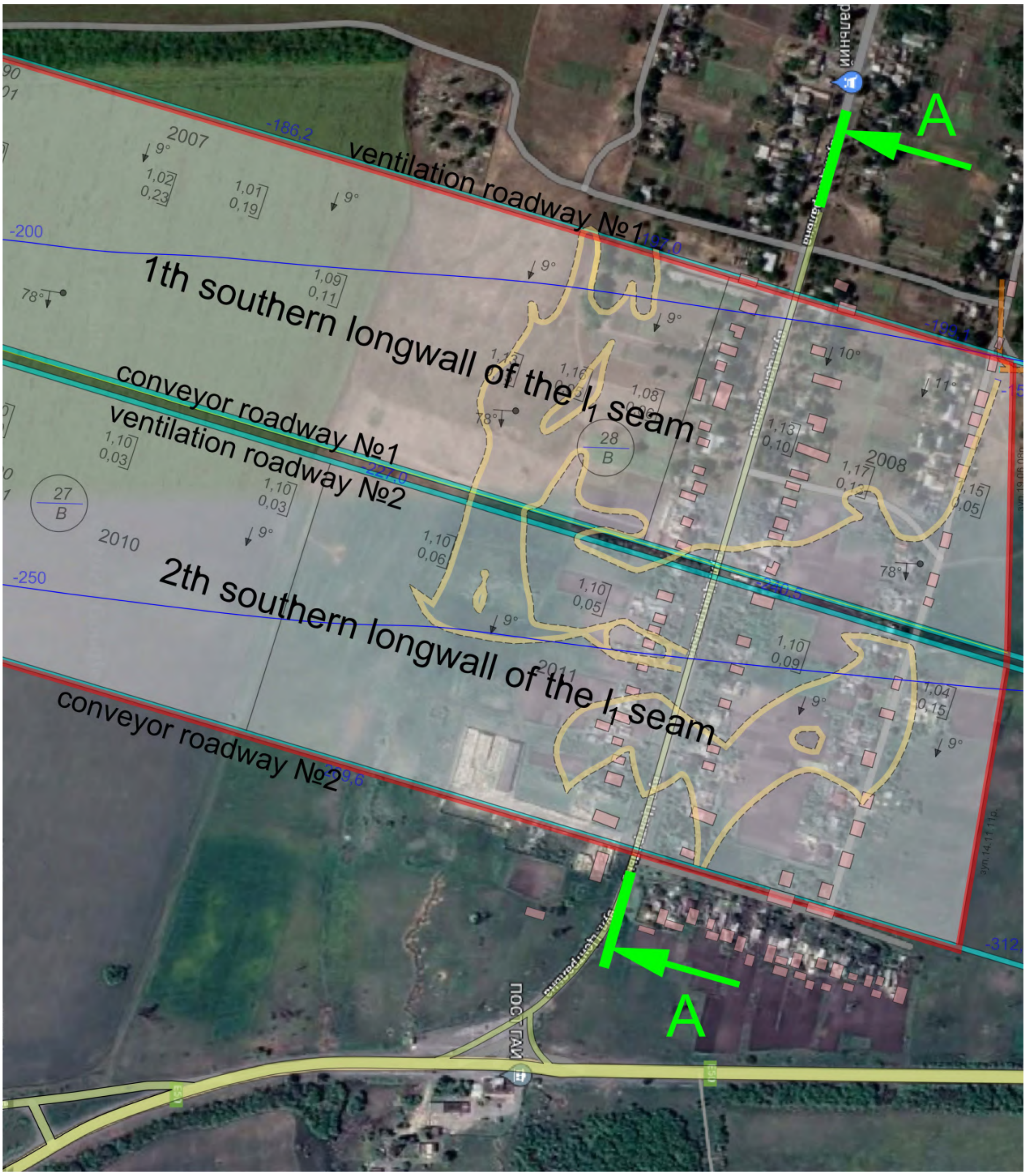
The initial data for numerical simulation (modulus of elasticity, Poisson's ratio, cohesion value, angle of internal friction and angle of dilatancy) were taken from the cadastre of physical rock properties [28], according to the stratigraphic column. At the same time, the rocks were modeled as heterogeneous. The variation of the physical and mechanical properties of rocks along and across the layering was determined according to the methodology proposed Sakhno et al [29], which is generally consistent with the research of Rzhevsky.

The excessive detail during modeling was avoided trough grouping of rock properties according to their strength, using average index. The rock strata were combined into groups, where their strength difference was less than 25%. This approach is permissible, since the aim of simulation was not to study the deformation of the rock strata in the undermine zone, but to analyze the surface subsidence.

The general view of the finite element model with its dimensions is shown in figure 3.

The study consisted of three cases:

(i) basic model (no flooding);



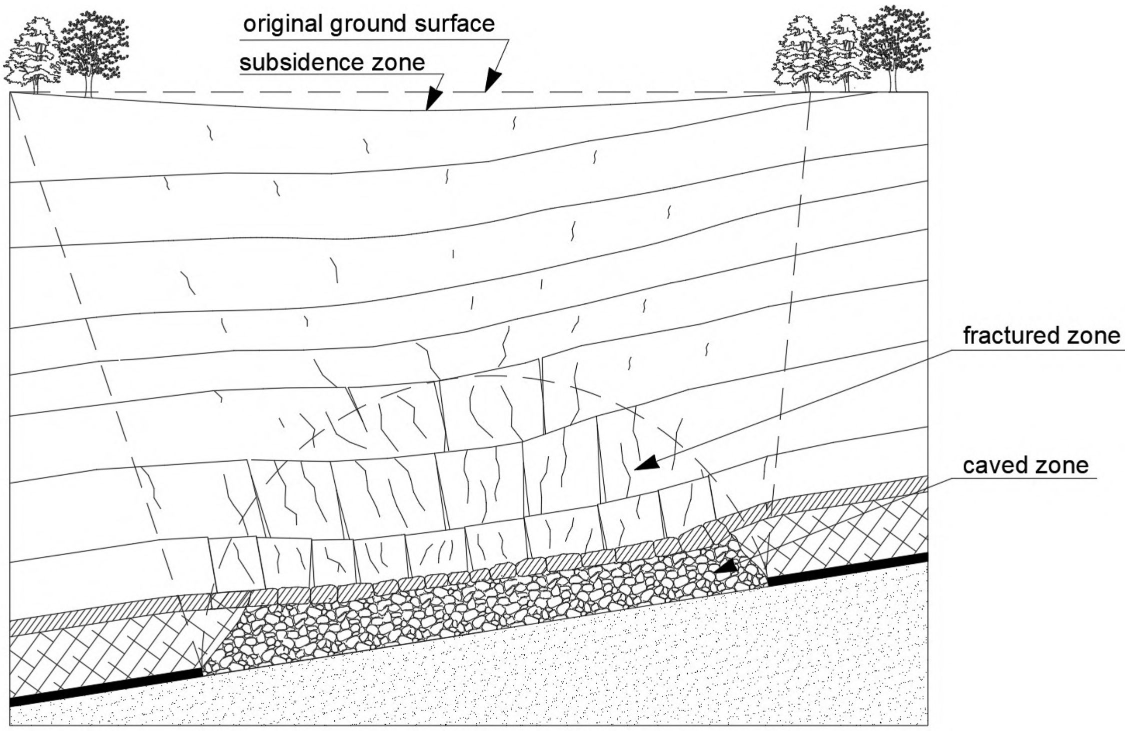
(*A-A – section line*)

Figure 1. Mine plan and the surface objects.

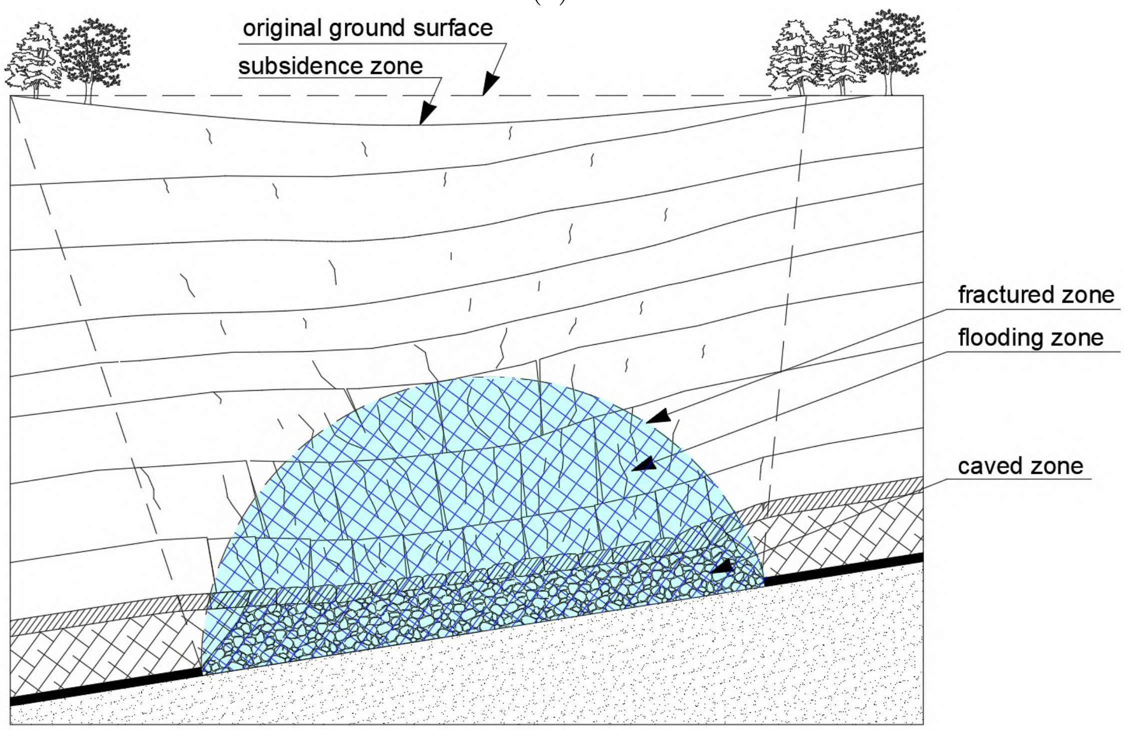
(ii) model with flooding of 40% of the fractured zone;

(iii) model with flooding of 100% of the fractured zone.

The geometry and grid of finite elements in the models were the same, which made it impossible to accumulate calculation errors.

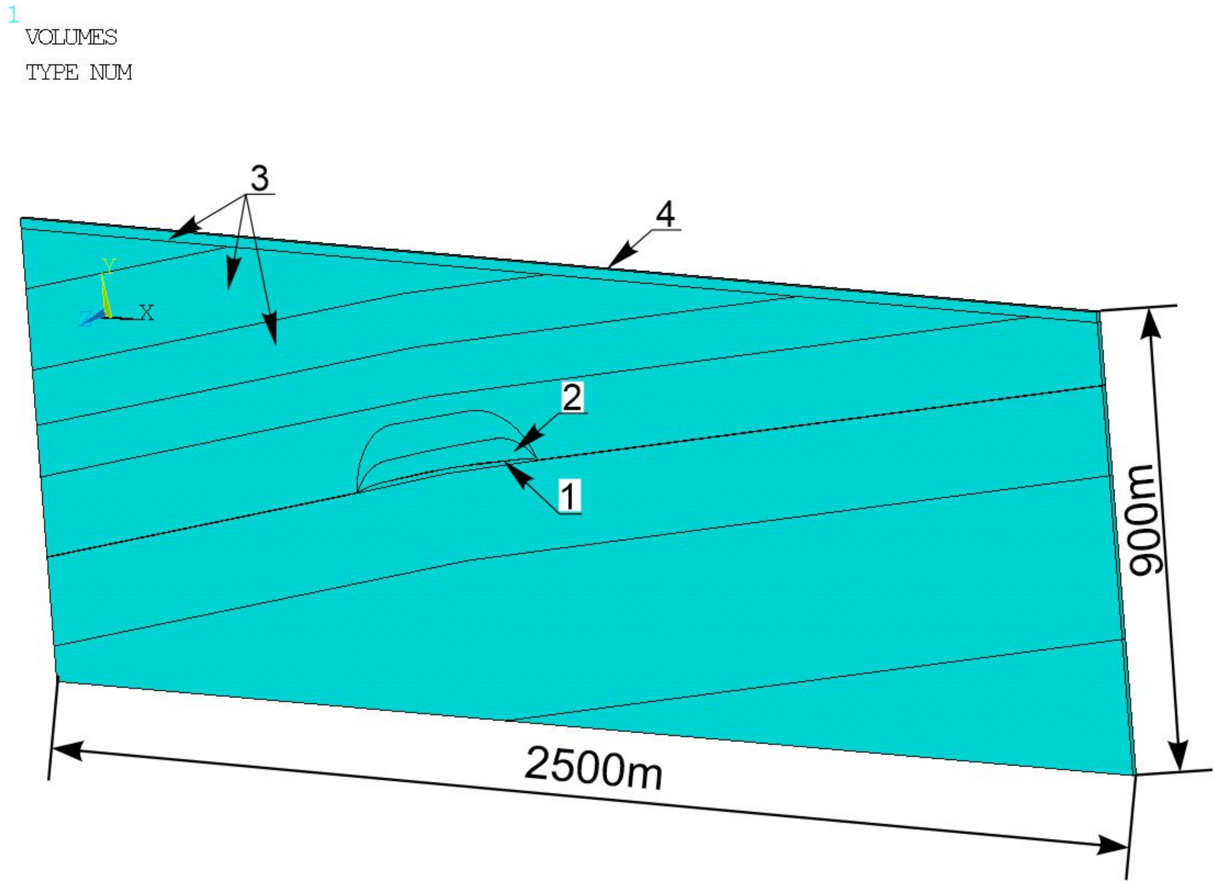


(a)



(b)

Figure 2. Overburden deformation zones caused by longwall subsidence: (a) before flooding; (b) after flooding.



(*1 – caved zone; 2 – fractured zone; 3 – rock strata; 4 – ground surface*)

Figure 3. General view of numerical model geometry.

The simulation was carried out step by step as follows.

Step 1: Loading the model with gravity, followed by writing the values of stresses and displacements in all nodes of the model to a file using the Inistate command in ADPL.

Step 2: Reading the recorded file with values and recalculating the model for zeroing displacement. In this case, a situation of the initial stress-strain state of the strata was obtained.

Step 3: Modeling of coal excavation and formation of caved zones and fractured zone (basic model).

Step 4: Simulation of flooding 40% of the fractured zone.

Step 5: Simulation of flooding 100% of the fractured zone. The patterns of vertical displacements in the model, which correspond to the described steps, are shown in figure 4.

To simulate the behavior of rocks in the caved zone and fractured zone, the correction of their properties was used, taking into account the fracturing. For this, the Hoek-Brown criterion was used [30].

To take into account the influence of moisture on the rock properties, the deformation modulus in the flooding zone was reduced and Poissons ratio was increase. The basis of this decision is

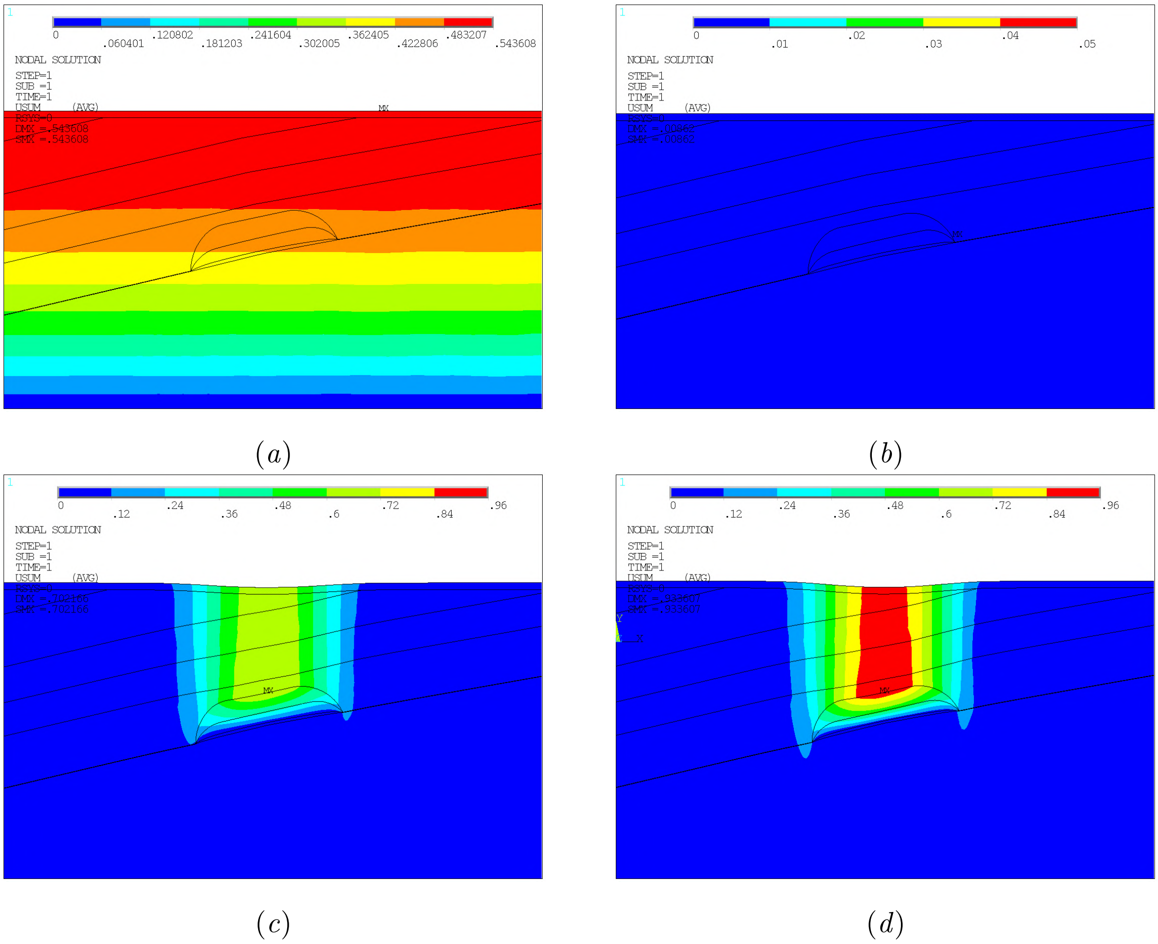


Figure 4. Displacement patterns with a step-by-step modeling (displacement scale 20:1): (*a*) step 1; (*b*) step 2; (*c*) step 3; (*d*) step 5.

numerous experimental study [31–34]. Obviously, this influence depends on many factors, first of all, on the type of rocks and the degree of water saturation.

Sakhno et al. [35] showed that the deformation modulus for wet rock (E_w) can be expressed as:

$$E_w = E1.0076e^{-0.239\Delta w}, \text{GPa} \tag{1}$$

where: E – deformation modulus of dry rock (MPa); Δw – water increase (%).

The rise of water level was simulated, therefore the maximum water saturation of the rocks was taken. The properties of the rocks that were used during the simulation are shown in table 1.

4. Results and discussion

The adequacy of any mathematical model is characterized by the divergence of the results obtained during its use with real values in-situ. Since monitoring of surface subsidence was not carried out in this study, the verification and calibration of the basic model were performed with predicted subsidence determined by normative document DSTU 101.00159226.001-2003 [22].

A safe depth 440m was calculated. It has been established that mining was conducted above the level of safe depth. That may cause subsidence of the surface exceeding the permissible ones.

Table 1. Input data for numerical modelling.

	Density, kg/m^3	Elastic modulus, MPa	Poissons ratio	Cohesion, MPa	Angle of internal friction, deg	Dilatancy angle, deg
			Quaternary rock mass			
1	2100	15-9	0.25	5.5-4.7	25	5
			Bed rock mass (continuous zone)			
2	2500	20-9	0.17-0.25	6.4-5.35	32	32
			Caved zone (dry)			
3	2500	0.6	0.25	–	–	–
			Fractured zone (dry)			
4	2500	0.9	0.25	–	–	–
			Caved zone (wet)			
5	2500	0.4	0.30	–	–	–
			Fractured zone (wet)			
6	2500	0.6	0.30	–	–	–

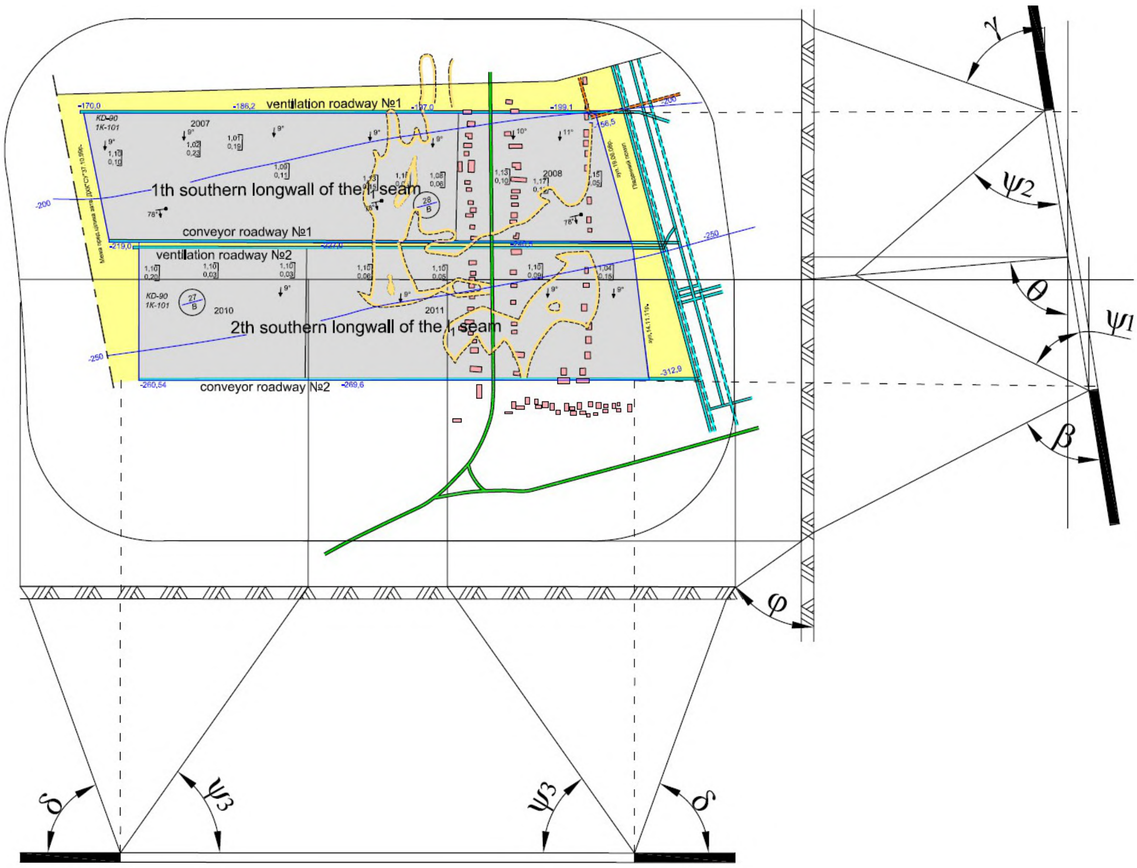


Figure 5. Subsidence trough (in accordance with DSTU 101.00159226.001-2003 [22]).

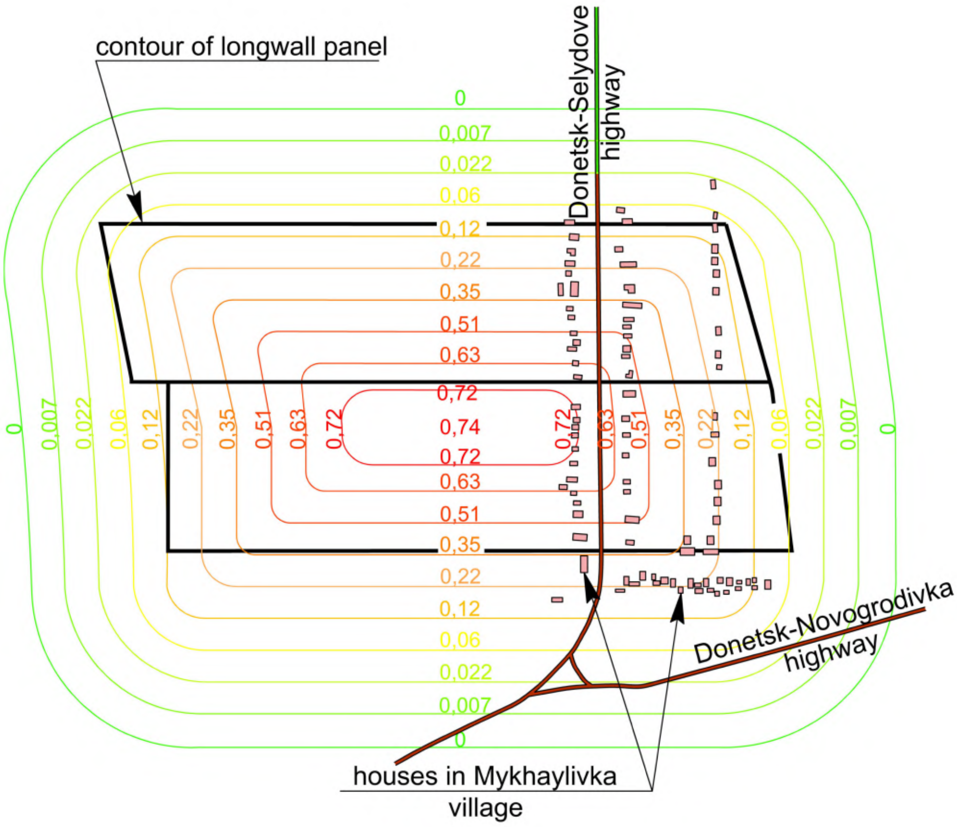


Figure 6. Isolines of subsidence caused by undermining.

The results of the graphic calculation of the subsidence trough with the corresponding cross sections are shown in figure 5.

Initial parameters of the subsidence process [22]: limit angle $\delta = 70^o, \gamma = 70^o, \beta = 63^o, \psi_1 = 55^o, \psi_2 = 58^o, \psi_3 = 55^o$, maximum subsidence angle $\theta = 83^o$, maximum possible surface subsidence $\eta_{max} = 0.74$ m.

Plan of subsidence isolines caused by undermining of 1th and 2th southern longwalls of the seam l_1 is shown in figure 6.

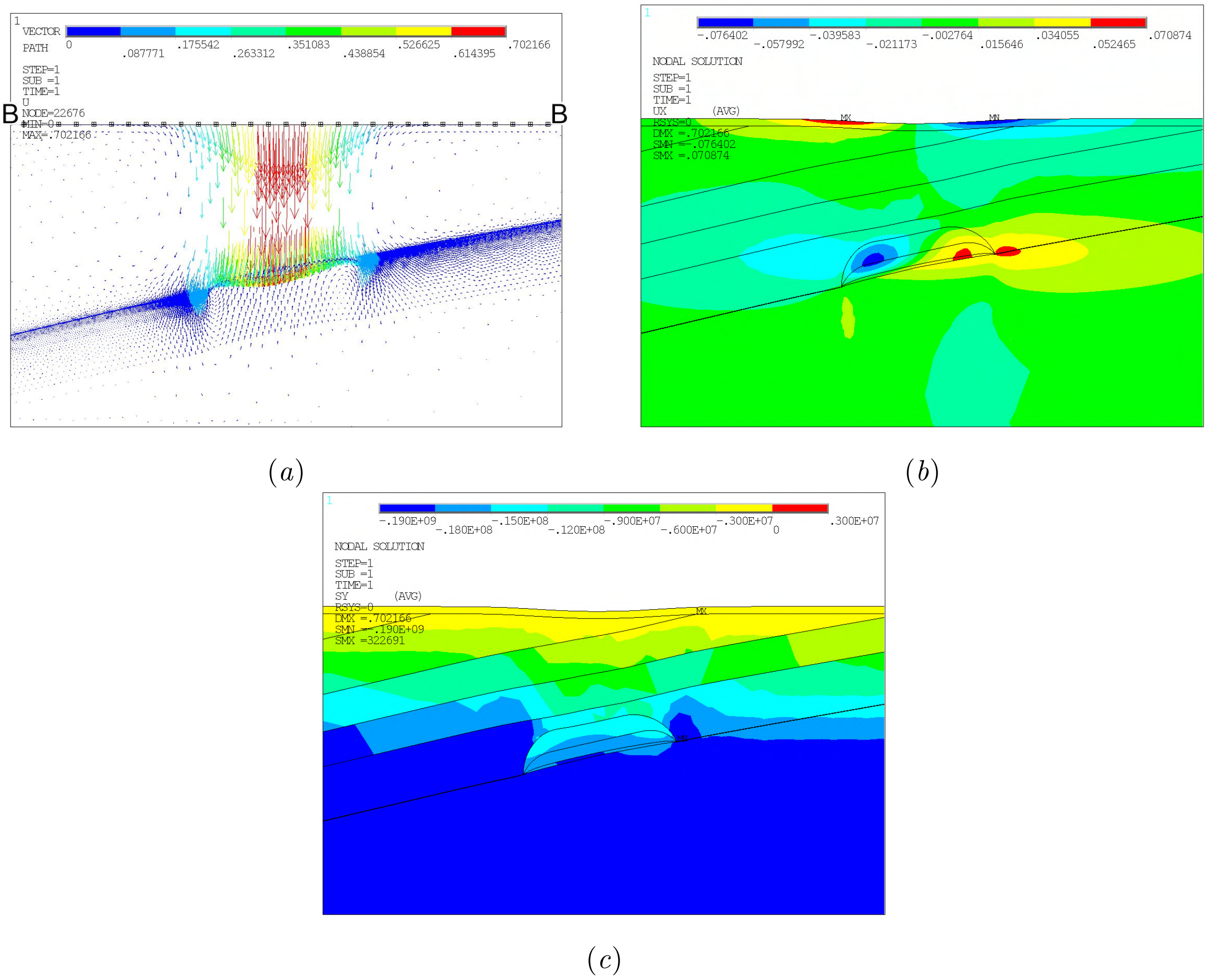
As can be seen from figure 6, Donetsk-Novogrodivka highway, Donetsk-Selydove highway and Mykhailivka village are located in the mining influence zone. Some houses are located above the zone of maximal subsidence. The results of numerical simulation for the base model are shown in figure 7.

The scale for converting colors in digital format is shown in the upper parts of the figures. Numerical designations on the scale line of figure 7a, b are given in meters, in figure 7c – in Pascals. In order to more clear display of the subsidence trough boundaries, the scale of displacement in figure 7 is increased by 20 times.

At the first stage of simulation process, the numerical model was calibrated. For this purpose, graphs of displacements and curvature along the B-B line were made (figure 8) and their convergence with the results of settlement calculations according to the DSTU 101.00159226.001-2003 was checked [22].

As can be seen from figure 8, the numerical model allows to adequately describe the process of surface deformation.

The maximal vertical displacement in the numerical model is 735 mm. The maximal vertical



(*B-B – monitoring line*)

Figure 7. Base model simulation results (displacement scale 20:1): (*a*) pattern of displacement vectors; (*b*) pattern of horizontal displacements; (*c*) pattern of vertical stress.

displacement that was calculated according to DSTU 101.00159226.001-2003 [22] is 738 mm. In the model, the displacement at the border of the trough subsidence is equal to 7 mm at a distance of 40 m from the longwall axis, according to normative document [22] – 380 m. Thus, the respective divergences are –0.2% and +4%.

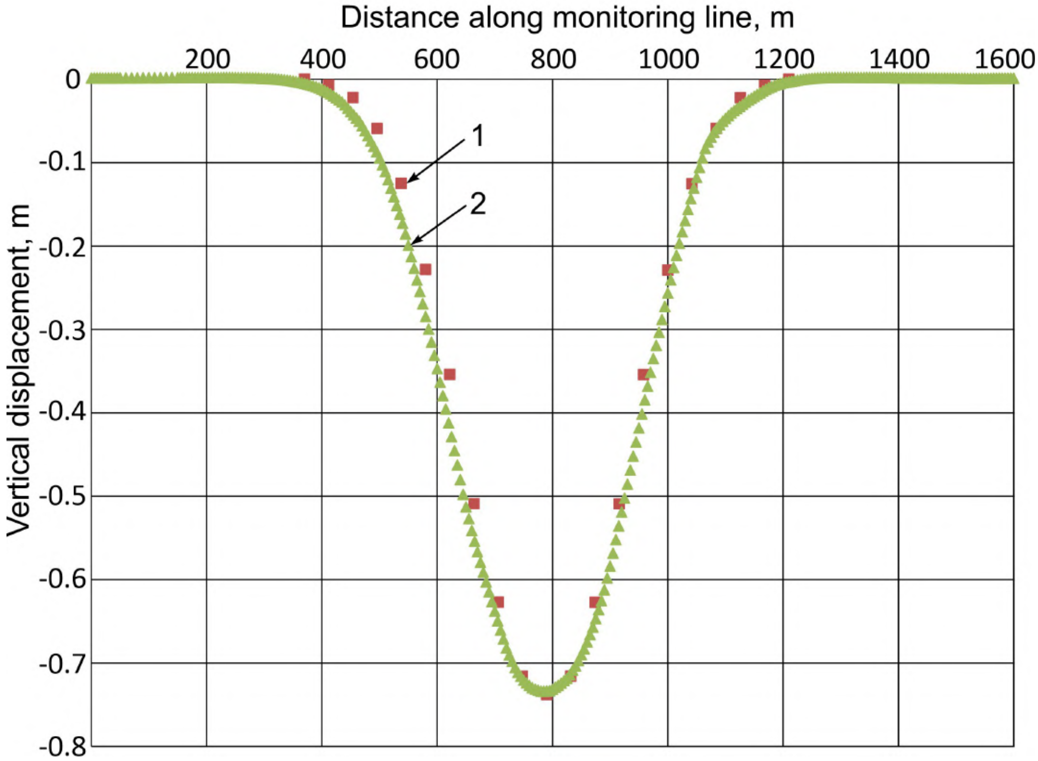
The maximal inclination in the model is 0.003082, calculated according to [22] – 0.003029; the divergence is 1.7%. The mean squared error of the simulation results for the inclination factor is 5.23%, for the vertical displacement factor is 5.1%. Such results are quite acceptable.

In the next stage of modeling, flooding of the longwall goaf was simulated in two stages (40% and 100% of the total height of the fractured zone). The simulation results are shown in figure 9.

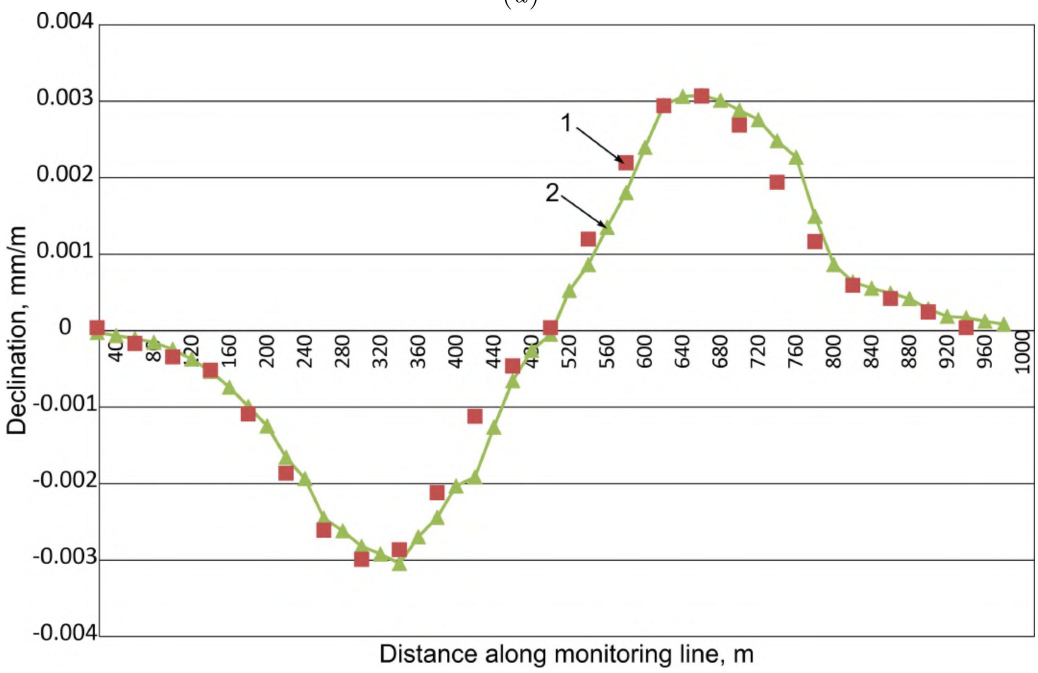
The graphs of subsidence, inclinations and curvatures are shown in figure 10.

After the first step of flooding, the maximal subsidence increases to 821 mm, i.e. by 86 mm (11.7%), after the second step of flooding – to 900 mm, i.e. by 165 mm (22.4%). At the same time, the length of the subsidence trough during flooding increases by only 5 m (1.3%).

The simulation result shows that the length of the subsidence trough increases less significant than the maximal subsidence, thus, flooding provokes the increase of inclination, curvatures and horizontal displacements.



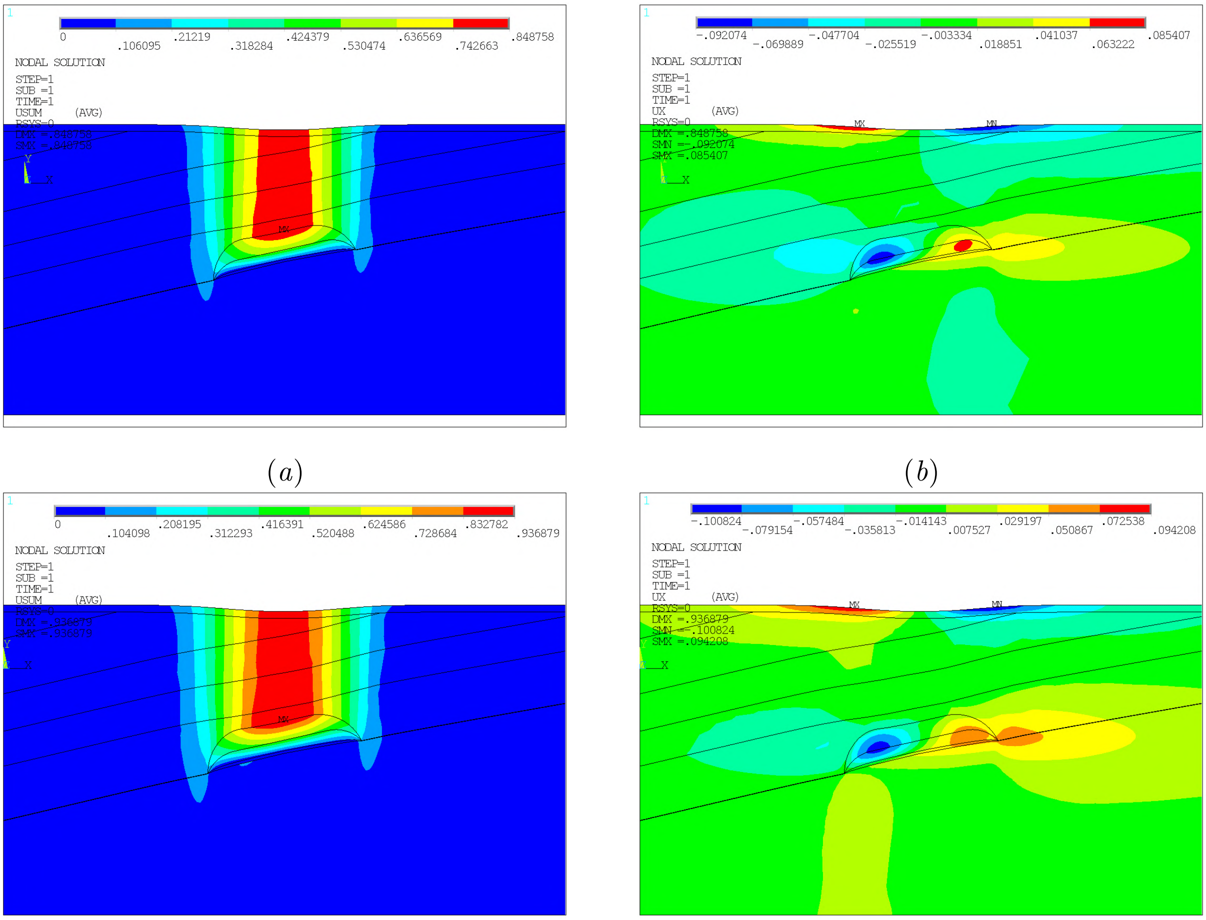
(a)



(b)

(1 – according to the DSTU 101.00159226.001-2003 [22], 2 – numerical simulation results)

Figure 8. Graphs of vertical displacements (a) and inclination (b) along the B-B line.



(a) (b)

(c) (d)

Figure 9. Distribution of vertical and horizontal displacement during the first (a, b) and second (c, d) steps of flooding (displacement scale 20:1).

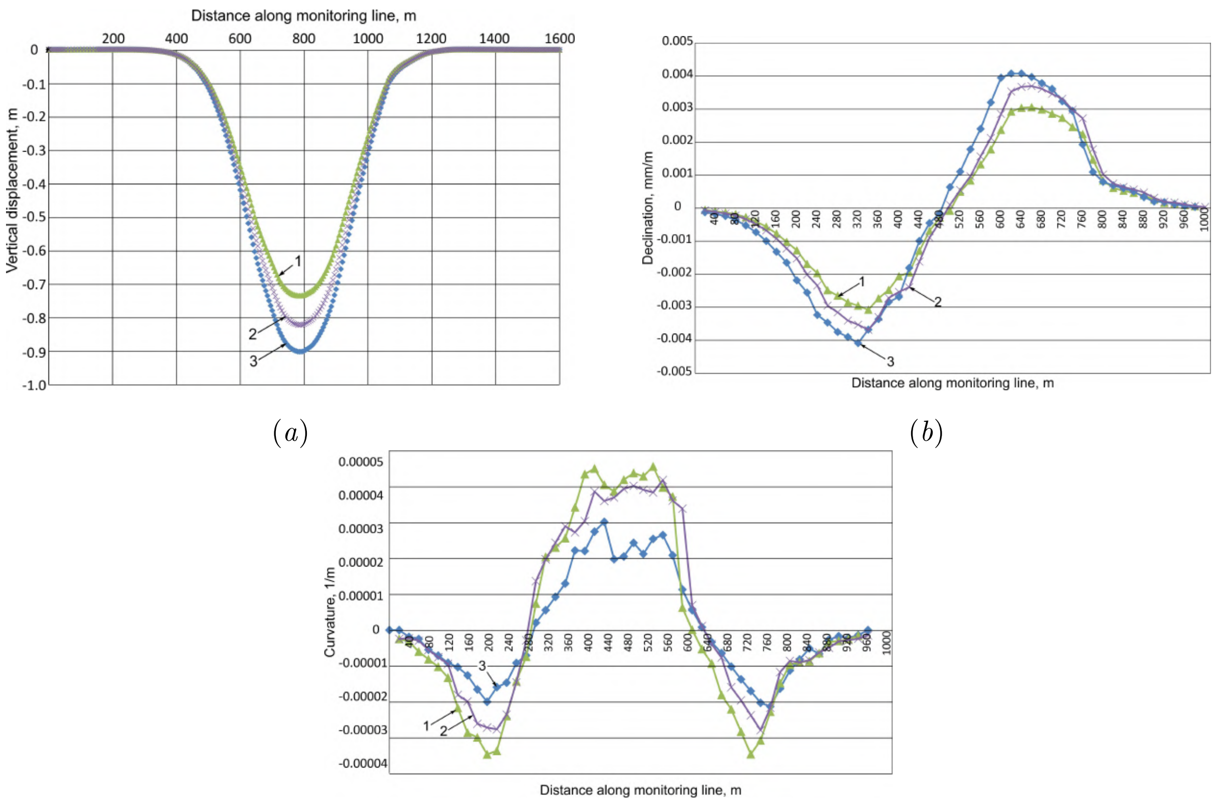
The maximal inclination as a result of full flooding of the fractured zone, according to the simulation results, increases from 0.00302 to 0.00406 (by 34.4%). Flooding by 40% of the height of the fractured zone leads to an increase in maximal inclination from 0.00302 to 0.00368 (by 21.8%).

Curvature at the edges of the trough subsidence increases from 0.0000200 to 0.0000348, and in the central part of the trough – from 0.00003032 to 0.00004525, by 74% and 49% respectively.

The increase of maximal subsidence, inclination and curvatures occurs disproportionately to the goaf flooding height. Thus, flooding by 40% of the height of fractured zone leads to an increase of maximal subsidence on 52.1%, maximal inclination on 63.4% and maximal curvature on 48.9% respectively.

Thus, flooding leads to activation of surface deformation. This cause increased hazards for surface objects, especially at the extension trough zone. For the case study, the risk of destruction of houses in the Mykhailivka village, which located in the subsidense prone land, increases. In addition, the risk of destruction of the Donetsk - Selidove highway, which is located in the area of subsidence impact, increases.

The current study is based on the results of numerical modeling and represents a theoretical solution. In the future, field monitoring is planned to confirm and verify the obtained results.



(*a*) (*b*)

(*c*)

(1 – before flooding, 2 after flooding of 40% of the fractured zone, 3 – after flooding of 100% of the fractured zone.)

Figure 10. The graphs of subsidence (*a*), inclinations (*b*) and curvatures (*c*) in the undermining zone (along monitoring line B-B) (displacement scale 20:1).

Modern methods of the surface monitoring allow making large areas observation quickly [3, 36]. This significantly save time and human resources for field measurement.

This study opens up opportunities for development of different ways of surface subsidence control. The goaf backfilling is one of the most well-known control methods of strata deformation. Backfilling in Ukraine is carried out mainly for the conditions of ore deposits [37, 38]. The theoretical studies are also carried out for coal deposits [39–41]. The presented study is planned to develop in this direction.

5. Conclusions

This paper presents the numerical simulation results of the longwall goaf flooding impact on the activation of ground movement during excavation of thin coal seams.

Based on the results of this investigation, the following conclusions can be drawn:

1. One of the characteristic phenomena with which the future of the Ukrainian Donbas is connected is the flooding of the longwalls goaf of coal mines. The risks of mine roadways flooding are increasing as a result of military operations in Ukraine. Therefore, save of the surface objects from the negative impact of undermining is becoming one of the urgent problems. Timely planning and development of control methods require an adequate prediction of subsidence evolution caused by mine roadways flooding.

2. The finite element model was created in the Ansys code, which allows to predict the ground movement caused by underground coal mining. The error of the trough subsidence calculation did not exceed 6%.
3. It was showed that the longwall goaf flooding leads to the activation of the subsidence process. As a result of the analysis, it was proved that the flooding on the full height of the fractured zone above the longwall goaf leads to an increase in subsidence by 22.4%, while the length of the trough increase by 1.3%. Maximal inclination increases by 34.4%, and maximal curvature – by 74%. This contributes to a significant increase in hazards for surface infrastructure located on the edges of the subsidence trough. Risk decrease for surface infrastructure can be ensured by timely prediction of subsidence and implementation of surface controlling methods.

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References
[1] Zhang Y, Cao S, Gao R, Guo S and Lan L 2018 *Sustainability* **10**(5) 1636 ISSN 2071-1050 URL https://doi.org/10.3390/su10051636
[2] Pysmennyi S, Chukharev S, Kyelgyenbai K, Mutambo V and Matsui A 2022 *IOP Conference Series: Earth and Environmental Science* **1049**(1) 012008 URL https://dx.doi.org/10.1088/1755-1315/1049/1/012008
[3] Zhang K, Bai L, Wang P and Zhu Z 2021 *Advances in Civil Engineering* **2021** 5599925 URL https://doi.org/10.1155/2021/5599925
[4] Guney A and Gul M 2019 *International Journal of Mining, Reclamation and Environment* **33**(7) 445–461 URL https://doi.org/10.1080/17480930.2018.1443691
[5] Zhao H, Ma F, Zhang Y and Guo J 2013 *Environmental Earth Sciences* **68**(7) 1903–1911 ISSN 1866-6299 URL https://doi.org/10.1007/s12665-012-1877-7
[6] Nazarenko V and Stelmaschuk V 2009 *Problemi girskogo tisku* **18**(8)
[7] Zhou Y and Yu X 2022 *Applied Sciences* **12**(18) 9057 ISSN 2076-3417 URL https://doi.org/10.3390/app12189057
[8] Yanli H, Jixiong Z, Baifu A and Qiang Z 2011 *Journal of Mining Science* **47**(5) 618–627 ISSN 1573-8736 URL https://doi.org/10.1134/S1062739147050108
[9] Stupnik M, Kalinichenko V, Pysmennyi S, Fedko M and Kalinichenko O 2016 *Mining of Mineral Deposits* **10**(3) 618627 URL https://doi.org/10.15407/mining10.03.046
[10] Karmis M, Agioutantis Z and Andrews K 2008 Enhancing Mine Subsidence Prediction and Control Methodologies *27th International Conference on Ground Control in Mining* pp 131–136 URL https://energy.vt.edu/content/dam/energy_vt_edu/vccer-publications/2008_WVU.pdf
[11] Agioutantis Z, Newman C, Leon G B J and Karmis M 2016 *Mining Engineering* **68**(3) 28–37 URL https://aries.energy.vt.edu/content/dam/aries_energy_vt_edu/journal_paper_enviromentally_responsible_mining_technology/Agioutantis_Z_etal_Mining%20Engineering_2016.pdf
[12] Agioutantis Z G and Karmis M 2013 Recent Developments on Surface Ground Strain Calculations due to Underground Mining in Appalachia *32nd International Conference on Ground Control in Mining* pp 214–219 URL https://aries.energy.vt.edu/content/dam/aries_energy_vt_edu/conference_enviromentally_responsible_mining_technology/Agioutantis_Z_Karmis_ME_32nd%20International%20Conference%20on%20Ground%20Control%20in%20Mining_2013.pdf
[13] 2018 Surface Deformation Prediction System (SDPS) Software URL https://www.osmre.gov/programs/technical-innovation-and-professional-services/services/sdps
[14] Jeromel G, Medved M and Likar J 2010 *Acta geotechnica Slovenica* **7**(1) 30–45 URL https://www.researchgate.net/publication/279562323
[15] Zhao K, Xu N, Mei G and Tian H 2016 *SpringerPlus* **5**(1) 977 ISSN 2193-1801 URL https://doi.org/10.1186/s40064-016-2609-3

[16] Marian D P, Onica I, Marian R R and Floarea D A 2020 *Sustainability* **12**(4) 1598 ISSN 2071-1050 URL https://doi.org/10.3390/su12041598
[17] Sakhno I, Grischenkov N and Golubev F 2013 *Naukovi pratsi UKRNDMI NAN Ukrayini* **13** 209–219
[18] Grischenkov N and Golubev F 2014 *Nauk. problemy nedropolzovaniya* 154–157
[19] Pysmennyi S, Fedko M, Shvaher N and Chukharev S 2020 *E3S Web of Conferences* **201**(01022) URL https://doi.org/10.1051/e3sconf/202020101022
[20] Stupnik M, Kalinichenko O, Kalinichenko V, Pysmennyi S and Morhun O 2018 *Mining of Mineral Deposits* **12**(4) 5662 URL https://doi.org/10.15407/mining12.04.056
[21] Zhang Z, Mei G and Xu N 2022 *Journal of Rock Mechanics and Geotechnical Engineering* **14**(1) 219–231 ISSN 1674-7755 URL https://doi.org/10.1016/j.jrmge.2021.11.001
[22] MFEU 2004 *Pravyla pidrobky budivel', sporud i pryrodnyx objektiv pry vydobuvanni vuhillja pidzemnym sposobom* DSTU 101.00159226.001-2003 (Alan)
[23] Booth C 2006 *Environmental Geology* **49**(6) 796–803 ISSN 1432-0495 URL https://doi.org/10.1007/s00254-006-0173-9
[24] Dawkins A 2003 Potential Management and Rehabilitation Requirements of Environmental Effects From Longwall Subsidence on Streams, Lakes and Groundwater Systems *Proceedings of the 2003 Coal Operators' Conference* ed Aziz N and Kininmonth B p 117124 URL https://ro.uow.edu.au/coal/166/
[25] Qiu B and Luo Y 2013 Applications of subsurface subsidence model to study longwall subsidence influences on overburden hydrological system *Proc. Symp. Environmental Considerations in Energy Production* URL https://www.researchgate.net/publication/266740930
[26] Fan K, He J, Li W and Chen W 2022 *Rock Mechanics and Rock Engineering* **55**(7) 4015–4030 ISSN 1434-453X URL https://doi.org/10.1007/s00603-022-02855-2
[27] Zhang C, Tu S and Zhao Y 2019 *Environmental Earth Sciences* **78**(1) 27 ISSN 1866-6299 URL https://doi.org/10.1007/s12665-018-8037-7
[28] Melnikov N, Rzhevskiy V and Protodyakonov M 1975 *Spravochnik (kadastr) fizicheskih svoystv gornih porod* (Nedra)
[29] Sakhno I G, Molodetskyi A V and Sakhno S V 2018 *Naukovyi Visnyk NHU* (5) 48–53 URL https://doi.org/10.29202/nvngu/2018-5/4
[30] Hoek E, Carranza-Torres C and Corkum B 2002 Hoek-Brown failure criterion 2002 edition *Proceedings of the 5th North American Rock Mechanics Symposium and the 17th Tunnelling Association of Canada Conference* vol 1 pp 267–273 URL https://www.rocscience.com/assets/resources/learning/hoek/Hoek-Brown-Failure-Criterion-2002.pdf
[31] Zhou Z, Cai X, Cao W, Li X and Xiong C 2016 *Rock Mechanics and Rock Engineering* **49**(8) 3009–3025 ISSN 1434-453X URL https://doi.org/10.1007/s00603-016-0987-z
[32] Romana M and Vasarhelyi B 2007 A Discussion On the Decrease of Unconfined Compressive Strength Between Saturated And Dry Rock Samples (*ISRM Congress* vol All Days) pp ISRM–11CONGRESS–2007–031 URL https://onepetro.org/isrmcongress/proceedings-pdf/CONGRESS07/All-CONGRESS07/ISRM-11CONGRESS-2007-031/1832726/isrm-11congress-2007-031.pdf
[33] Makowski P, Ostrowski Ł and Bocki P 2017 *Geology, Geophysics and Environment* **43**(1) 43 URL https://doi.org/10.7494/geol.2017.43.1.43
[34] Yang J, Li L and Lian H 2020 *PLOS ONE* **15**(8) 1–16 URL https://doi.org/10.1371/journal.pone.0237909
[35] Sakhno I, Sakhno S, Skyrda A and Popova O 2022 *Geofluids* **2022** 3855799 URL https://doi.org/10.1155/2022/3855799
[36] Kalinichenko V, Dolgikh O, Dolgikh L and Pysmennyi S 2020 *Mining of Mineral Deposits* **14**(4) 31–39 URL https://doi.org/10.33271/mining14.04.031
[37] Pysmenniy S, Shvager N, Shepel O, Kovbyk K and Dolgikh O 2020 *E3S Web of Conferences* **166** 02006 URL https://doi.org/10.1051/e3sconf/202016602006
[38] Stupnik N, Kalinichenko V, Pismennij S and Kalinichenko E 2015 Features of underlying levels opening at arsellormittal kryvyic rih underground mine *New Developments in Mining Engineering 2015: Theoretical and Practical Solutions of Mineral Resources Mining* ed Pivnyak G, Bondarenko V and Kovalevska I (London: CRC Press) pp 39–44 URL https://doi.org/10.1201/b19901-8
[39] Petlovanyi M, Malashkevych D, Sai K, Bulat I and Popovych V 2021 *Mining of Mineral Deposits* **15**(4) 122–129 URL https://doi.org/10.33271/mining15.04.122
[40] Nehrii S, Nehrii T, Piskurska H, Fesenko E, Pavlov Y and Surzhenko A 2021 *Journal of Mining and Environment* **12**(4) 953–967 URL http://ea.donntu.edu.ua/handle/123456789/33598
[41] Sakhno I G, Sakhno S V and Kamenets V I 2022 *IOP Conference Series: Earth and Environmental Science* **1049**(1) 012011 URL https://doi.org/10.1088/1755-1315/1049/1/012011

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Interaction of conical monolithic thin-walled reinforced concrete shells with the soil of the foundation

Interaction of conical monolithic thin-walled reinforced concrete shells with the soil of the foundation

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Abstract. Conical monolithic thin-walled reinforced concrete blocks (shells) can be used as foundations for frame structures and buildings with load-bearing walls. As an analogue of columnar foundations, this type has the advantage of the speed of installation. It almost wholly excludes earthwork and formwork from the technological process, provided that the physical and mechanical properties of the soil base are improved. Shells are immersed in the supporting soil base with the help of dynamic or static loading. Additional soil base compaction occurs due to interaction with the conical outer surface of the shells. The work aims to develop the theoretical foundations for modelling, mathematical description and the possibility of optimizing the process of sinking monolithic thin-walled spatial reinforced concrete shells that model foundations for low-rise technological or residential facilities. Based on the analysis of the "hammer-head-shell-soil" system, an elastic-viscous-plastic model with an attached soil mass was developed and presented, which is used as a basis for developing a system of nonlinear differential equations of the second order. The article provides recommendations on the impact of structural and technological factors on the failure rate and the contact stresses in the hammer-shell zone. The following factors have a significant influence on the failure of the shell: the height of the hammer lift, soil resistance, and the ratio of the masses of the hammer and the shell. The effect of shock-absorbing elements is insignificant. The greatest influence on the magnitude of the contact forces in the zone of the hammer-shell has: the height of the fall of the hammer and the stiffness of the resilient gasket.

1. Formulation of the problem

Monolithic and prefabricated reinforced concrete foundations traditionally used at present, along with known advantages, have great complexity of erection on the construction site, high material consumption and, accordingly, cost. The use of monolithic thin-walled spatial reinforced concrete shells (MTWSRCS) as foundations for low-rise technological or residential objects is economically feasible from the point of view of reducing the volume of earthworks by up to 90%, abandoning the use of formwork, shortening the time for the concrete to gain strength. In addition, the use of MTWSRCS, in comparison with classical types and methods of laying foundations, allows you to significantly reduce the costs of concrete, reinforcement, and labor costs, which ultimately leads to a decrease in the estimated cost of zero-cycle works by up to 40% [1–7].

The issues of interaction processes of MTWSRCS with the soil of the foundation during dynamic or static immersion, as well as during the operation of the building, remain insufficiently researched and highlighted in the scientific literature.

2. Analysis of the latest sources of research and publications

There are some close, according to the physics of the process, the results of research on establishing the resistance of the foundation soils with the dynamic method of sinking classical reinforced concrete piles into it, conducted by: B.V. Bakholdin, L.Ya. Ginsburg, D.D. Barkan, etc. [8–12]. Most researchers recommend determining the soil base's resistance by considering the so-called viscosity coefficient.

In the work of L.R. Stavnitzer established the existence of a critical rate of soil deformation, beyond which the magnitude of the reaction of the soil base practically does not depend on the rate of its deformation. B.V. Bakholdin, L.Ya. Ginzburg proved that the value of the critical rate of deformation of the soil relative to the piles depends on the static resistance of the soil.

Immersion in the soil of MTWSRCS, similar to the process of immersion of a classic reinforced concrete pile, the layers of the soil base are pushed to the sides and bent down. Due to the significantly greater conicity of MTWSRCS compared to the old one, soil deformations are brighter and visually noticeable. This leads to additional compaction of the soil under the conical part of the MTWSRCS, which is accompanied by the destruction of the natural structure of the upper layers of the soil, their mixing and partial bulging upwards. The result is an artificial soil base with improved physical and mechanical properties and correspondingly higher bearing capacity. The prospects of this type of foundation with MTWSRCS for soil foundations that are not prone to frost heave, are not over moistened and are not located in a climatic zone with a long period of negative average daily outdoor air temperatures should be noted.

3. The goal of the work

Based on practical experience using monolithic thin-walled spatial reinforced concrete shells as foundations for low-rise technological or residential facilities, develop theoretical foundations for modelling, mathematical description and the possibility of optimizing the immersion process.

4. Research results

Immersion of MTWSRCS is possible by impact and static load in the form of discrete or continuous gradual loading. Immersion by impact is a complex energy process, during which the potential energy of the hammer is transformed into the kinetic energy of the impact, which leads to the overcoming of the resistance forces of the soil base to the final and elastic movements under the surface of the MTWSRCS [2, 3, 11–13].

At the same time, the impact energy developed by the falling load (hammer) is partially lost during the co-impact through the damper between the hammer and the shell, shaking the surrounding soil of the base, and only a part of it determines the final movements of the MTWSRCS.

During the impact of the shock load, the elastic deformation of the head C_1 , then the shell C_2 itself, and the soil of the base C_3 occurs, and only after that does the final vertical movement (immersion) of shell E occurs. After the shock pulse is exhausted, the elastic deformations are restored. Thus, the total elastic deformations are equal to:

$$C = C_1 + C_2 + C_3. \tag{1}$$

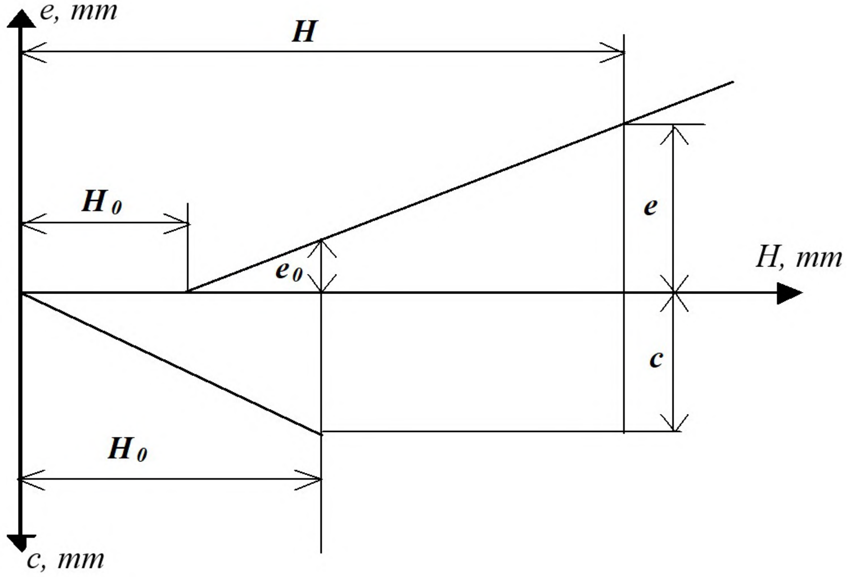

Figure 1. Scheme of the dependence of C and E failures on the height of the fall of the hammer H.

The values of C_1 and C_2 are usually small and can be neglected in many cases, i.e. take $C = C_3$. In the idealized schemes of changes in C and E as the impact energy of the hammer ϵ increases, the elastic part of failure C increases at $E = 0$, until it reaches the limit value C (figure 1). With a further increase in ϵ , the value of C remains constant. The final failure of E begins to increase. Thus, the ultimate elastic deformation of soil C does not depend on the immersion parameters Q and H and is a soil characteristic.

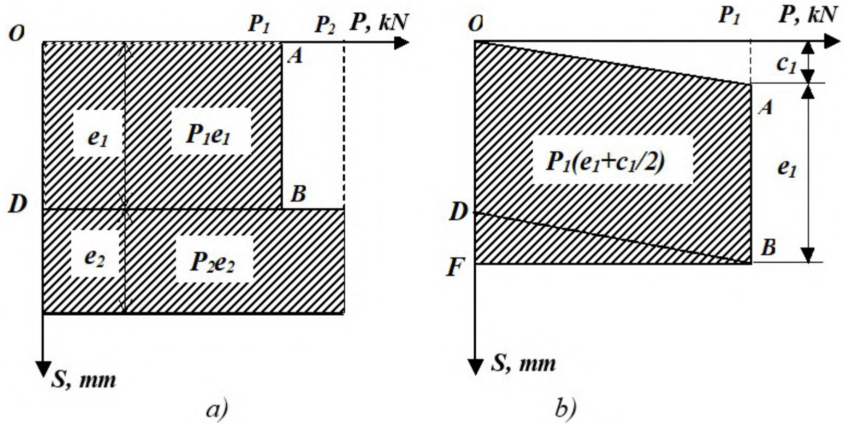

Figure 2. Dependence between the frontal resistance to movement of the shell P and its settlement S with different models of interaction: a) - plastic model; b) - elastic-plastic model.

The dynamic nature of the load application, which qualitatively changes depending on the ratio of the three phases of the soil base, significantly influences the soil's deformation and resistance to the immersion of the shells. Due to the impossibility of considering all the features of the upper layers of the soil base of the construction site and obtaining accurate analytical expressions of dynamic resistance, it seems appropriate to use modelling methods for this purpose. At the same time, it is proposed to apply simple models that could reflect only the main properties of the system, and a large number of temporary features would be taken into account in a generalized way or through the values of calculated indicators. To simplify this model, the initial state of the soil and the features of its changes during deformation may not be taken into account. Just to reflect the final influence of the features of this soil on the development of resistance forces may be reflected. Such simplest soil models for the analysis of the "hammer-head-shell-soil" system are plastic and elastically plastic [9, 11–15] (figure 2).

The plastic model is built considering the following assumptions (figure 2, a). It is an absolutely solid body, and the soil surrounding it is motionless. Resistance on the side surface P_b, etc. friction between the side surfaces of the shell and the soil, reduced to equivalent to all types of Coulomb dry friction (it is assumed that P_b, does not depend on the speed of movement of the shell).

As the tests showed, reducing the dynamic side friction to the equivalent dry friction makes it possible to obtain fairly stable soil resistance values.

The frontal resistance P_l is represented by a pinched weightless bottom. Overcoming the friction that develops on the side surface, the shell affects the bottom, which sinks if the force applied to it exceeds P_l.

The relationship between the frontal resistance to the movement of the shell and its subsidence is given in a simplified form - in the form of a broken line OAB, and it is assumed that the force P_l does not depend on the speed of movement of the shell. The area of the OABD diagram represents the work for one cycle of P_e (figure 2, a). Despite its simplicity, this scheme can be quite useful, as it does not require setting many uncertain parameters of elasticity and viscosity.

The elastic-plastic model is distinguished by the presence of elastic ties that simulate the elasticity of the soil and intermediate elements (figure 2, b). At this research stage, it is assumed that the elasticity of the soil is manifested mainly at the point of contact of the end of the shell with the soil [16–19]. Therefore, the assumption that the lateral resistance to immersion is characterized by dry friction remains valid for the scheme.

The mechanical model of frontal resistance is simplified as a bottom with a linear spring. When the casing is struck, the elastic deformation of the soil OA (compression of the spring) first occurs, and after the force in it reaches the value of the frontal resistance P_l, irreversible compression of the bottom AB begins (figure 2, b). After the load is over, the BD is restored. This graph generally shows well the interaction of the shell with the soil.

The positive properties of this model are also that when using the energy approach to determine energy costs, i.e. the area of the force-displacement diagram, the contours of this diagram, as well as the condition that $C = 0$ does not affect the accuracy of the results.

The considered model does not take into account the influence of soil inertia, which is quite significant. Therefore, for further clarification, an elastic-plastic model with an attached soil mass is adopted (figure 3, c). In this model, the surrounding attached soil mass is represented by an equivalent elastic body resting on elastic supports. In this case, the body's weight is equal to the attached soil's weight.

When the shell moves after impact, the attached mass moves together with the shell until the elastic forces of the springs reach the values of the resistance on the side surface P_b. After that, the shell begins to slide relative to these elements. Further interaction is similar to the interaction of the previous model.

The elastic-viscous-plastic model (figure 3, d) allows you to consider the soil's viscous resistance. Further, it is possible to clarify the nature of the change in the frontal resistance of the soil depending on the settlement during loading and unloading, which means applying instead of a simple Prandtl elastic-plastic model, an elastic-plastic model with compaction, etc. Thus, the number of possible variants of dynamic models can be pretty significant. These models will more and more fully reflect the influence of the main factors and their role in the

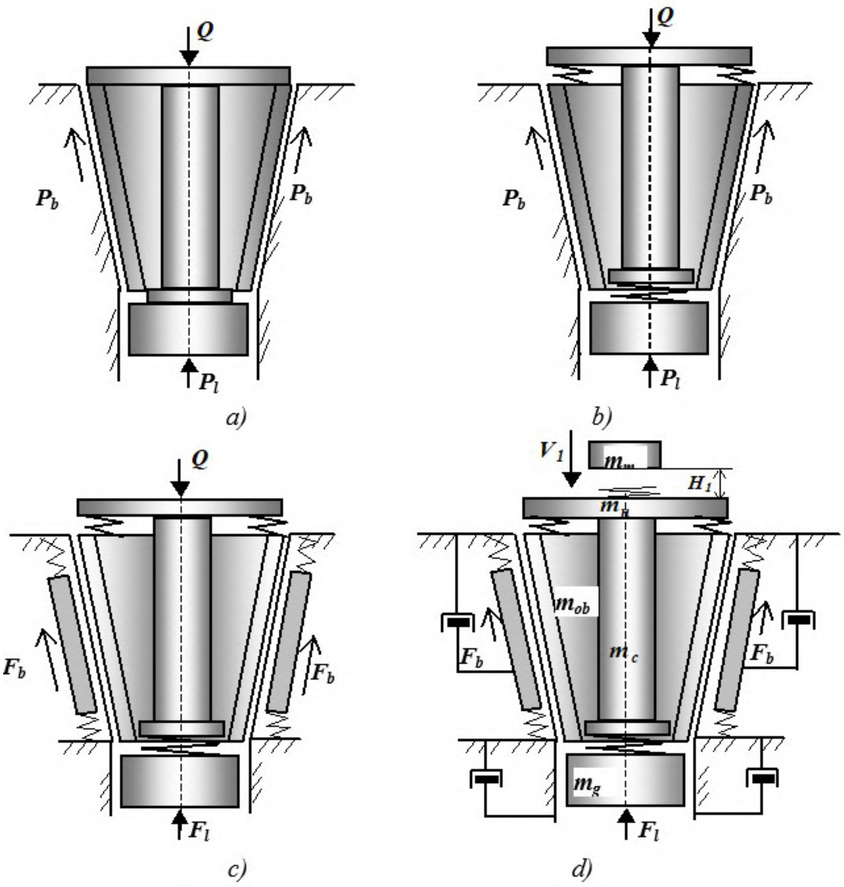

Figure 3. Dynamic models of the "hammer-head-shell-soil" system: a) - plastic model; b) – elastic-plastic model; c) – elastic-plastic model with attached soil mass; d) – elastic-viscous-plastic model with attached soil mass.

immersion process. In all models analyzed above, the shell is considered as a completely rigid body. However, upon impact, the shell has an elastic deformation. In addition, the usual impact on the shell is performed through the elastic headband. Therefore, a spring can also represent the shell and the headband's elasticity.

Evaluating the possibility of using complex models for practical calculations, it should be pointed out that currently, there is not a sufficient amount of experimental data for a reasonable assignment of the numerical values of many indicators characterizing these models. In addition, the obtained mathematical expressions of the interaction of the "hammer-shell-soil" system will become more and more complex with the complexity of the models, and this complexity will not always contribute to an increase in accuracy, i.e. practical purposes. Taking this into account, for further research, it is most appropriate to use an elastic-viscous-plastic model considering the attached mass of the soil and the elasticity of the shell and the head (figure 3, d). This scheme allows you to take into account the change in the value of the attached mass of the soil and the change in the nature of the interaction in connection with this.

Thus, the dynamic model of the "hammer-head-shell-soil" system with elastic-viscous-plastic resistance of the soil is presented as follows. The elastic shell, which is in the soil, is struck with a hard undeformed hammer through the elastic head.

Under the influence of the impact, the shell acquires a reserve of kinetic energy, which is spent on overcoming soil resistance: with each impact, the shell sinks, initially elastically deforming the soil by the amount C, and then the plate moves in the soil by the amount of final failure E. Elastic deformations are restored after each impact. Each blow is considered as a single one, isolated from others, which means that before each subsequent impact, the shell, hammer and soil are at rest. The shock is absorbed by the reduced mass of the shell, taking into account part of the mass of the soil attached to it, and the subsequent movement is carried out only by the shell. The hammer impact effect is represented as the transfer of some part of the kinetic energy of the impact ϵ, which goes directly to the immersion of the shell [16–18, 20].

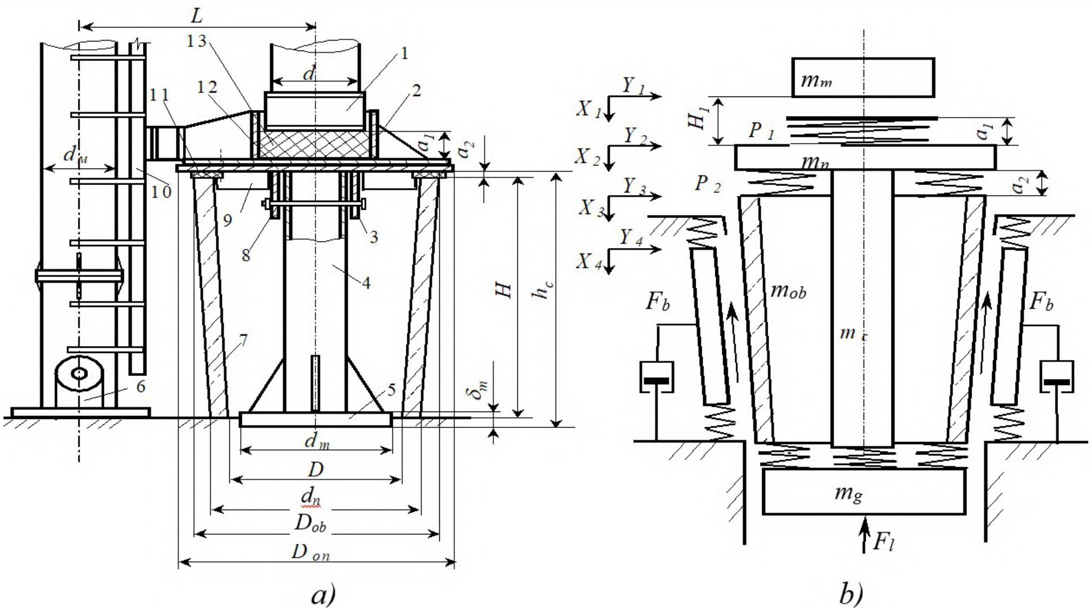

Figure 4. "Hammer-head-shell-soil" system: a) - real system; b) – calculation scheme: 1 - hammer; 2 - headrest; 3 - conductor; 4 - core; 5 - tamping plate; 6 - mast; 7 - shell; 8 - finger; 9 - stops; 10 - guides; 11 - gasket; 12 - transmission plate; 13 - shock absorber.

For the development of a mathematical model of the process of immersion in the ground base of conical-reinforced concrete shells, a calculation scheme is proposed (figure 4).

The mathematical model of this process is a system of nonlinear differential equations consisting of the equations of the "hammer-head" and "shell-soil" subsystems, which must be solved jointly.

The mathematical model "hammer-head-shell-soil" is a system of nonlinear differential equations of the second order:

$$\begin{cases} m_2 d^2X_2/dt^2 = Q_2 + P_{12} - P_{23}, \\ (m_3 + m_4)\, d^2X_3/dt^2 = Q_3 + Q_4 + P_{23} - F_l - F_b, \quad F_b \le R_b \\ X_3 = X_4, \\ m_1 d^2X_1/dt^2 = Q_1 - P_{12}, \\ m_3 d^2X_3/dt^2 = Q_3 + Q_4 + P_{23} - F_l - F_b, \\ m_4 d^2X_4/dt^2 = Q_4 + F_b - K_b X_4, \qquad F_b < R_b \end{cases} \tag{2}$$

where m_1, m_2, m_3, m_4 - are the masses of the hammer, head, and shell, respectively core and load;

Q_1, Q_2, Q_3, Q_4 - respectively, the weight of the hammer, head, and shell core and soil;

P_{12}, P_{23} - respectively, the forces acting on the contacts of the bodies, which collide;
X_1, X_2, X_3, X_4 - are, respectively, the coordinates of the hammer, head, shell and soil;
F_l, F_b - frontal and lateral soil resistance, respectively;
R_b - is the ultimate resistance of the soil on the side surface.

The solution of this system of equations gives the displacement and speed of all bodies, as well as the value of the forces acting on the contacts of colliding bodies at any moment in time.

Mathematical model (2) belongs to the class of simulation models, as it simulates in detail the submersion of shells by impact load. This nature of the model allows you to use it to study the process of computer immersion. In addition, implementing full-scale experiments on the immersion of shells is a rather expensive method that requires a lot of machine time.

Experience shows that the most interesting for practice is the study of the influence of the following factors on the immersion process:

- ultimate resistance of the shell on the soil;
- the ratio of the mass of the striking part to the mass of the submerged shell;
- the thickness of the elastic gasket in the headrest;
- lifting height of the impact part.

Wood or conveyor rubber can be used as cushioning material in the headrest. The soil's stiffness depends on the value of the lateral resistance so that the elastic failure does not exceed 1 cm. This value of elastic failure is most often encountered in practice.

Calculations on a computer were carried out for a hammer with a striking part weighing 500 kg. Mathematical planning of the experiment was used to organize calculations on a computer. The four-factor Hartley-Cohn plan was adopted [21,22]. In order to obtain analytical dependencies between the parameters of the studied system, a correlation analysis of the obtained data was carried out. The regression equations of the type were used for the analysis:

$$y = A + \sum_{i=1}^{n} B_i X_i; \tag{3}$$

$$y = A + \sum_{i=1}^{n} \left(B_i X_i + C_i X_i^2\right); \tag{4}$$

$$y = A + \prod_{i=1}^{n} X_i^B. \tag{5}$$

Co-impacts in the "hammer-head-shell-base" system are characterized by forces that appear at the contacts of the elements that are in direct contact during the impact. On (figure 4, a, b, c) graphs of changes in time of these forces, calculated with the same initial data for some time, at a level of 0,03 s after the first contact of the hammer with the head, are given. The impulse of impact forces is characterized by several peaks and has a complex damping character. The contact of the shocking part with the head is irregular. Thus, for a period of 0,06 s, 11 co-impacts occurred at the "hammer-head" contact and ten at the "head-shell" contact.

This way, we can talk about the presence of an oscillatory process in the "hammer-head-shell-shell-soil" system. The headrest oscillations are unstable. This follows from the fact that during slow, quasi-static immersion, oscillations do not occur. They occur only during impact and die out as the load decreases.

In real conditions, due to the inevitable eccentricities of load application, the headrest carries out not only translational movement along the vertical axis, but also angular oscillations. In the mathematical model, following the accepted assumptions, all movements occur only along the

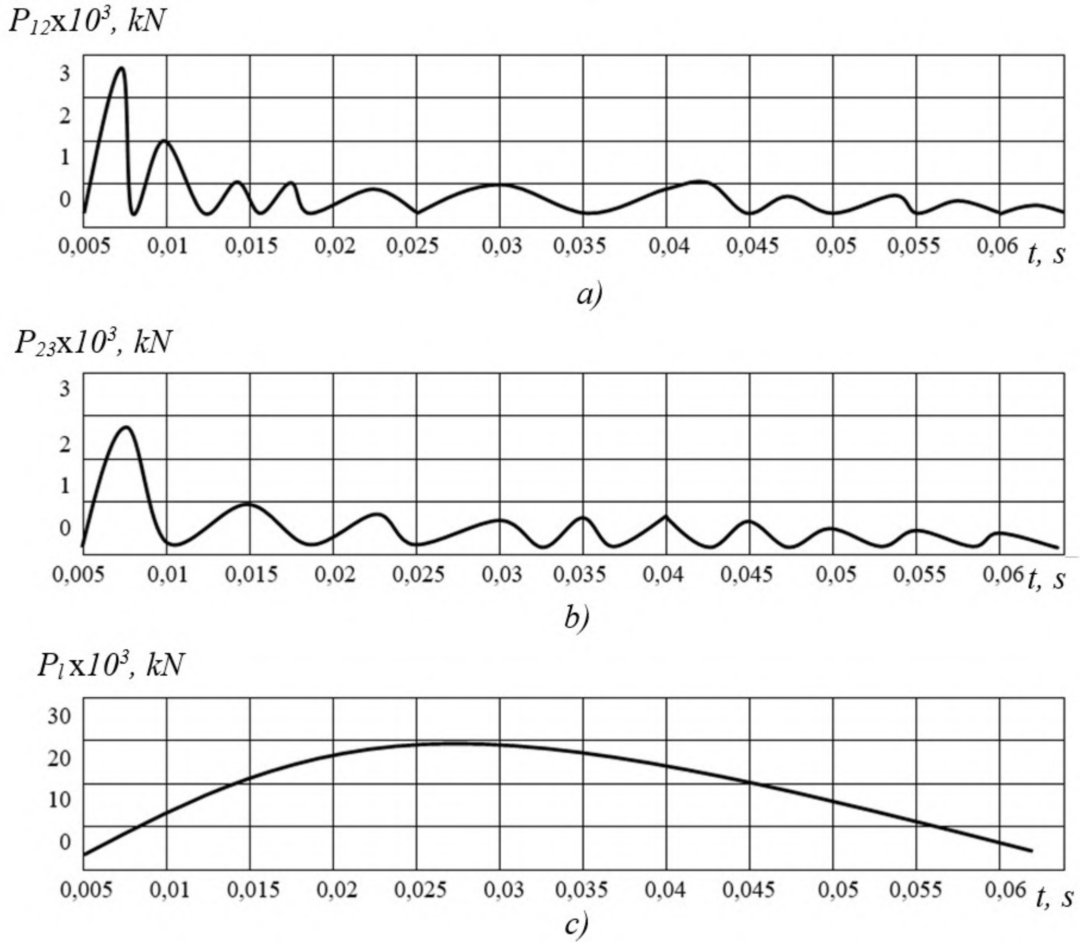

Figure 5. Forces acting on the contacts of colliding bodies: a) – hammer-head; b) – a head-shell; c) – is the frontal resistance of the soil.

vertical axis, so the graph of the impact force on the shell is divided into a number of separate co-impacts.

The observed multiple co-impacts of the headpiece with the shell are due to a significantly shorter period of the headpiece's own oscillations compared to the duration of the force impact. Therefore, the headpiece can be represented as a mechanical oscillator, brought out of equilibrium by mechanical co-impact with the striking part and then oscillating between two massive bodies: the striking part and the shell.

The regularities noted above were reflected in the correlation dependences for the impact force. The impact force on the "hammer-headset" and "headset-shell" contacts can be determined by the following dependencies:

$$P_1 = 314 m_m H_1 + 0.7R + 212\frac{m_m}{m_n} + 6131\frac{a_1}{S_1} + 950, \tag{6}$$

$$P_2 = 245 m_m H_1 + 0.97R + 522\frac{m_m}{m_c + m_{ob}} + 9231\frac{a_2}{S_2} + 637, \tag{7}$$

where $m_m, m_n, m_o b, m_c$ - are the masses of the hammer, head, shell, and core, respectively; a_1, S_1 , and a_2, S_2

- respectively, the thickness and area of the cushioning pads at the "hammer - headrest" and "headrest-shell" contacts;

H_1 - hammer lift height;

R - is soil resistance.

The correlation ratio of these formulas is at least 0,95. This testifies to the correct selection of varied parameters.

The analysis of the given dependencies shows that the force of the impact is mainly determined by the height of the impact part and the stiffness of the elastic gasket. The ratio of the masses of the hammer and the shell has a smaller influence on the immersion process. The influence of the physical and mechanical properties of the soil base is insignificant.

Despite the periodic nature of the force impact, the shell sinks into the soil base quite smoothly. This is explained by the significant mass of the shell, as well as the inertial stabilization properties of the soil base. The shell receives a positive acceleration under the influence of the first co-impact, and then the shell acceleration changes its sign, and its motion slows down.

For the value of the final failure, the best result is given by the dependence of the form:

$$\epsilon = 1.2 \frac{m_m H_1 \left(\frac{m_m}{m_n + m_c + m_o b}\right)^{0.2}}{R^{1.3} \left(10 a_1\right)^{0.64}}. \tag{8}$$

Analysis of the influence of various factors on the size of the failure shows that the impact of the stiffness of the shock absorber can be neglected since the reduction in failure when the thickness of the lining increases from 0,05 m to 0,25 m does not exceed 10%. Therefore, for practical purposes, dependence (8) can be simplified:

$$\epsilon = 1.2 \frac{m_m H_1 \left(\frac{m_n}{m_n + m_c + m_o b}\right)^{0.2}}{R^{1.3}}. \tag{9}$$

5. Conclusions

- The theoretical foundations for modelling, mathematical description and the possibility of optimization of the process of immersion of monolithic thin-walled spatial reinforced concrete shells in the soil environment have been developed.
- Evaluating the possibility of using complex models for practical calculations, it should be stated that, at the moment, there is not enough experimental data for a justified assignment of the numerical values of many indicators characterizing these models.
- The following factors significantly influence the failure of the shell: hammer lifting height, soil resistance, and the ratio of hammer and shell masses. The effect of shock-absorbing elements is insignificant.
- The most significant influence on the magnitude of the contact forces in the zone of the hammer-shell has: the height of the fall of the hammer and the stiffness of the elastic gasket. The influence of the ratio of the masses of the hammer and the shell, as well as the value of the soil resistance, is manifested to a much lesser extent.
- It is promising to establish the stress-deformation state of the soil base depending on the method of immersion and during the structure's life.

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References

[1] Poroshin O S 2011 *Vzaimodejstvie cilindricheskih binarnyh fundament-obolochek s glinistym gruntom osnovaniya. Dissertaciya na soiskanie uchyonoj stepeni kandidata tehnicheskih nauk po specialnosti 05.23.02 – osnovaniya i fundamenty, podzemnye sooruzheniya*

[2] Poroshin O S and Stepanov M A 2018 *Uchebnoe posobie. Binarnye fundamenty-obolochki v geotekhnicheskom stroitelstve*

[3] Panteleienko V I and Karpushyn S O 532–563 URL `https://doi.org/10.31713/m1121`

[4] Leontiev A and Efremov I 2018 *IOP Conference Series: Materials Science and Engineering* **365** 042031 ISSN 1757-899X publisher: IOP Publishing URL `https://dx.doi.org/10.1088/1757-899X/365/4/042031`

[5] Pronozin Y, Maltseva T, Poroshin O and Medvedeva A **265** 05032 ISSN 2261-236X publisher: EDP Sciences URL `https://www.matec-conferences.org/articles/matecconf/abs/2019/14/matecconf_gccets2018_05032/matecconf_gccets2018_05032.html`

[6] Feickert K A Thin shell foundations: Embodied carbon reduction through materially efficient geometry accepted: 2022-08-29T16:21:01Z URL `https://dspace.mit.edu/handle/1721.1/144920`

[7] Feickert K and Mueller C *Thin shell foundations: Historical review and future opportunities*

[8] Ishlynskyi A Y 1986 *Prikladnye zadachi mehaniki: v dvuh knigah. mehanika vyazkoplasticheskih i ne vpolne uprugih tel. Kniga pervaya, Knigi 1* (Nauka)

[9] Kolomiychuk G P, Maistrenko O F and Kolomiichuk V G 2020 *Modern technologies and methods of calculations in construction* 81–89 ISSN 2410-6208 number: 14 URL `https://eforum.lntu.edu.ua/index.php/construction/article/view/438`

[10] Zingoni A 2001 *Structural Engineering, Mechanics and Computation - 1st Edition* elsevier science ed (Elsevier Science) ISBN 978-0-08-054192-1 URL `https://www.elsevier.com/books/structural-engineering-mechanics-and-computation/zingoni/978-0-08-043948-8`

[11] Barkan D D 1962 *Dynamics of bases and foundations* (McGraw-Hill)

[12] Bauduin C M 2002 *Proceedings of the 9th International Conference on Piling and Deep Foundations DFI 2002* 301–312

[13] Arthur K O S and Charles W W N **48** 1616–1629 ISSN 0008-3674 publisher: NRC Research Press URL `https://cdnsciencepub.com/doi/abs/10.1139/t11-064`

[14] Abramovich H 2017 *Stability and Vibrations of Thin-Walled Composite Structures* elsevier science ed (Elsevier Science, Woodhead Publishing) ISBN 9780081004296 URL `https://www.elsevier.com/books/stability-and-vibrations-of-thin-walled-composite-structures/abramovich/978-0-08-100410-4`

[15] Frank R, Bauduin C and Driscoll R 2009 *Designers' Guide to Eurocode 7 : Geotechnical design* (Thomas Telford Limited)

[16] Godoy L A 1996 *Thin-Walled Structures with Structural Imperfections* (University of Puerto Rico at Mayaguez) ISBN 9780080542966 URL `https://www.elsevier.com/books/thin-walled-structures-with-structural-imperfections/godoy/978-0-08-042266-4`

[17] Zhenhai G 2014 *Principles of Reinforced Concrete* (Butterworth-Heinemann) ISBN 9780128009635 URL `https://www.elsevier.com/books/principles-of-reinforced-concrete/guo/978-0-12-800859-1`

[18] Panteleienko V I, Karpushyn S O, Chervonoshtan A L and Danylenko I O 2021 Stend dlya doslidzhennya protsesu zanurennya obolonok v hrunt v naturnykh umovakh. Patent ua-147293 Ukrayina, MPK (2021.01) E05D 13/00

[19] Zhakulin A S, Zhakulina A A, Zhusupbekov A Z, Nefedov V N, Tungatarov A M and Popov N I 2022 *Soil Mechanics and Foundation Engineering* **59** 224–228 ISSN 1573-9279 URL `https://doi.org/10.1007/s11204-022-09805-8`

[20] Panteleyenko V I, Chervonoshtan A L and Ihnatov A B 2006 Stend dlya doslidzhennya yakisnykh zakonomirnostey protsesu zanurennya modeley obolonok v hrunt Patent ua 147297 Ukraine, MPK (2006) E05D 13/00

[21] Kuneš J 2012 *Similarity and Modeling in Science and Engineering* (Cambridge: International Science Publishing Ltd) ISBN 978-1-907343-77-3 978-1-907343-78-0 URL `https://link.springer.com/10.1007/978-1-907343-78-0`

[22] Alanazi T 2018 *Construction and analysis of experimental designs* Ph.D. thesis RMIT University URL `https://researchrepository.rmit.edu.au/esploro/outputs/doctoral/Construction-and-analysis-of-experimental-designs/9921863780601341`

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Devices for automatic control of the quantity and quality of oil in tanks

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Devices for automatic control of the quantity and quality of oil in tanks

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Abstract. Currently, the most widely used devices for measuring the level of liquids (float and non-float). Float gauges are generally more accurate than non-float gauges. However, the operating conditions of float level gauges are much more difficult due to the difficult operating conditions of floats in an aggressive environment with a large amount of mechanical impurities. Automation tools used to measure the weight of oil and oil products should provide output information in a form convenient for further processing, at the same time, these devices should be structurally simple and applicable to existing types of tanks. The amount of oil in tanks can be determined in two ways: by measuring the level of oil and its specific gravity; by direct measurement of the weight of a liquid. Each of these methods has its own advantages and disadvantages.Currently, the most widely used devices for measuring the level of liquids (float and non-float). Float gauges are generally more accurate than non-float gauges. However, the operating conditions of float level gauges are much more difficult due to the difficult operating conditions of floats in an aggressive environment with a large amount of mechanical impurities. The choice of this or that device is determined by the specific conditions of its operation, the required measurement accuracy, aggressiveness of the liquid, etc. Limit switches are installed on the level gauge, which, when the liquid level in the tank reaches the upper or lower limit mark, turn on the alarm circuit. The principle of operation of the level gauge is based on measuring the increase in the electrical capacitance of sensors when they are filled with a substance (oil product) that has a dielectric constant that is different from the dielectric constant of air. The measurement accuracy is achieved by the fact that the entire measured level is divided into separate equal sections and is determined, among other factors, by the length of each section.

1. Introduction

The amount of oil in tanks can be determined in two ways: by measuring the level of oil and its specific gravity; by direct measurement of the weight of a liquid. Each of these methods has its own advantages and disadvantages.

Currently, the most widely used devices for measuring the level of liquids (float and non-float). Float gauges are generally more accurate than non-float gauges. However, the operating conditions of float level gauges are much more difficult due to the difficult operating conditions of floats in an aggressive environment with a large amount of mechanical impurities [1].

The choice of this or that device is determined by the specific conditions of its operation, the required measurement accuracy, aggressiveness of the liquid, etc. Limit switches are installed on the level gauge, which, when the liquid level in the tank reaches the upper or lower limit mark, turn on the alarm circuit.

The principle of operation of the level gauge is based on measuring the increase in the electrical capacitance of sensors when they are filled with a substance (oil product) that has a dielectric constant that is different from the dielectric constant of air [2, 3].

Statement of the problem. The measurement accuracy is achieved by the fact that the entire measured level is divided into separate equal sections and is determined, among other factors, by the length of each section. The device consists of a receiver and a five-digit drum counter that counts the liquid level in the tank. The block diagram of the capacitive level gauge is shown in figure 1.

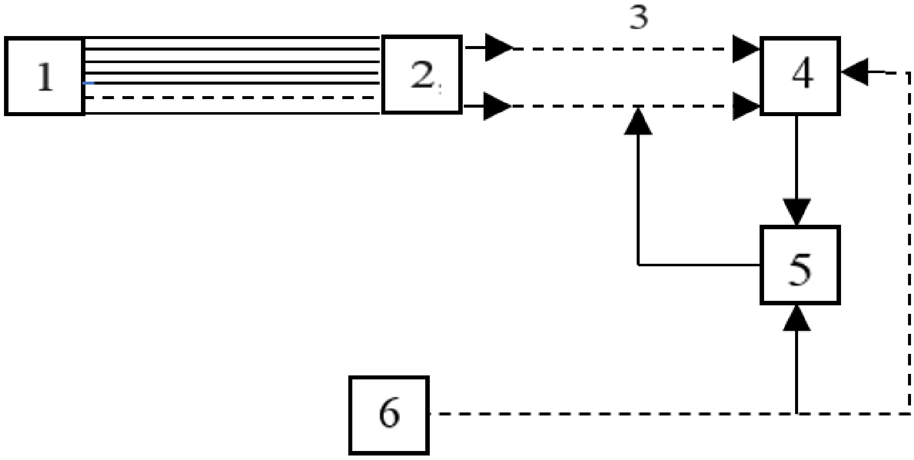

Figure 1. Block diagram of a discrete capacitive level transmitter.

It consists of a block of discrete sensors 1, a distribution block 2, a communication line 3, a measurement block 4, a control and registration block 5, and a power supply 6 [4].

The design of the sensors allows them to be attached to the fittings of the oil gauge glasses of the operated tanks. The sensors are pieces of two pipes of different diameters, located coaxially and isolated from each other by insulating washers. Sensors are grouped on a common pipe.

The pipe with sensors welded to it is inserted into the fittings of the oil gauge cocks. A threaded ledge emerges from the inner electrode of the sensor through an insulating sleeve, to which a filter is attached, consisting of an inductor, an isolation capacitor and a trimmer capacitor. The inductance of the filter, the capacitance of the sensor and the trimmer capacitor form a circuit tuned to the frequency of the generator of the measurement unit.

2. Results

The length of the section of each sensor is determined by the formula

$$1 \leq k\delta, \tag{1}$$

where l is the length of the section (sensor); k – coefficient; δ – permissible basic error.

For $k = 100$, the basic error is acceptable $\delta = 0.5$ cm, at $l \leq 50$ cm. Considering that the length of each gauge glass (between the respective fittings) is 1 m, then the number of sensors installed in each section should be $n_0 \geq 2$ [5, 6].

When manufacturing a level gauge with capacitive sensors, it is assumed that $n_0 = 3$; thus, 30 sensors were installed on the entire tank. The sensors are connected by a coaxial cable to the stepping finder of the distribution unit, installed at a distance of 10-15 m from them.

The distribution block is a piece of pipe with a flange and a cover. The step finder, when pulses are received from the programming device, alternately connects the sensors to the measurement unit.

The step finder with the measurement unit is also connected with a coaxial cable. To stabilize the parameters of the communication line and reduce additional errors associated with changes in temperature and humidity of the environment, the line is laid in a pipe, and part of the measuring unit to the step finder (distribution unit) is laid in the ground, and from the step finder to the sensor is covered with special thermal insulation.

The device is powered by 220 V AC mains. The measurement unit consists of a 100 W power transformer, a rectifier, and a discriminator generator [7].

An inductive circuit is connected to the anode of the generator lamp through a capacitor, which consists of two high-frequency transformers, the primary windings ($L1$ and $L2$) of which are connected in series. Each of the secondary windings $L3$ and $L4$ forms a circuit tuned to the frequency

$$f_1 = f_0 + (10 \div 20)\text{kHz}$$

Signals from the secondary windings go to the rectifier. The rectified currents are then fed for comparison to the input of an electronic potentiometer in the control unit. Parallel to the windings of the circuit $L3$ and $L4$, communication lines, additional inductances of low-pass filters, tuning capacitors and sensors are connected.

The variable load of the $L4$ winding is the capacitance of the main sensors, which are connected in turn to the winding by a stepper finder. Parallel to the winding $L3$, a control sensor located on the tank is permanently connected. Line connecting the control sensor with the winding $L3$, measuring block, has the same length as the line going to the main sensors and winding $L4$. Both lines are in the same conditions.

The above devices for automatic control of the amount of oil in tanks are based on the principle of measuring its level. Another method for determining the amount of oil in a reservoir is by weight.

The most convenient way to automate the measurement process is the so-called piezometric method (determining the weight of an oil product by its hydrostatic pressure).

Instruments designed for piezometric measurement of the weight of an oil product in a tank are compensatory pressure meters.

The operation of the device is based on the principle of force compensation, and discrete and continuous compensation is used to achieve the required high accuracy. Discrete compensation is carried out by weights, and continuous – by a lever with a movable weight.

As a sensitive element, which compares the measured and compensating parameters, a metal membrane with a rigid center, made of beryllium bronze, is used. The measurement error is mainly determined by the continuous compensation system, since discrete compensation is carried out with a high degree of accuracy. In this case, the total measurement error is the smaller, the more areas of discrete compensation for a given measurement range.

Indeed, if the entire range is divided into n parts, measured with a relative error δ_q and continuous compensation is performed with a relative error $\delta_{\text{continuous compensation}}$, then the largest total relative measurement error will be

$$\delta_0 = \frac{\delta_{\text{continuous compensation}} + \delta_{qn}}{1+n} \tag{2}$$

Having for the instrument $\delta_{\text{continuous compensation}} = 0.2\%$ and $n = 10$ and neglecting δ_q, because of its smallness compared to $\delta_{\text{continuous compensation}}$, we obtain the total compensation error up to $\delta = 0.02\%$. Then the accuracy of the device will be determined mainly by the stability of the characteristic and the sensitivity of the pressure element. The membrane used as a sensitive element has a linear dependence of the displacement force on the pressure within 0-1 kg/cm^2 and sensitivity 1-2 mm of water art., which provides the necessary measurement accuracy. The continuous compensation system is designed to create an accurate compensating force during the measurement process. During non-working hours, this system compensates for the weight of the plate, the elastic force of the rigid center, as well as the change in this force due to temperature and other external factors [8].

As noted above, during the measurement process, pulses are sent to dynamic errors from the system of discrete (coarse) and continuous (fine) compensation by the corresponding sensors. These pulses are fed to dynamic errors to the counting devices of the secondary device and the counting result is noted on the electroluminescent display. The block diagram of the secondary device is shown in the figure 2.

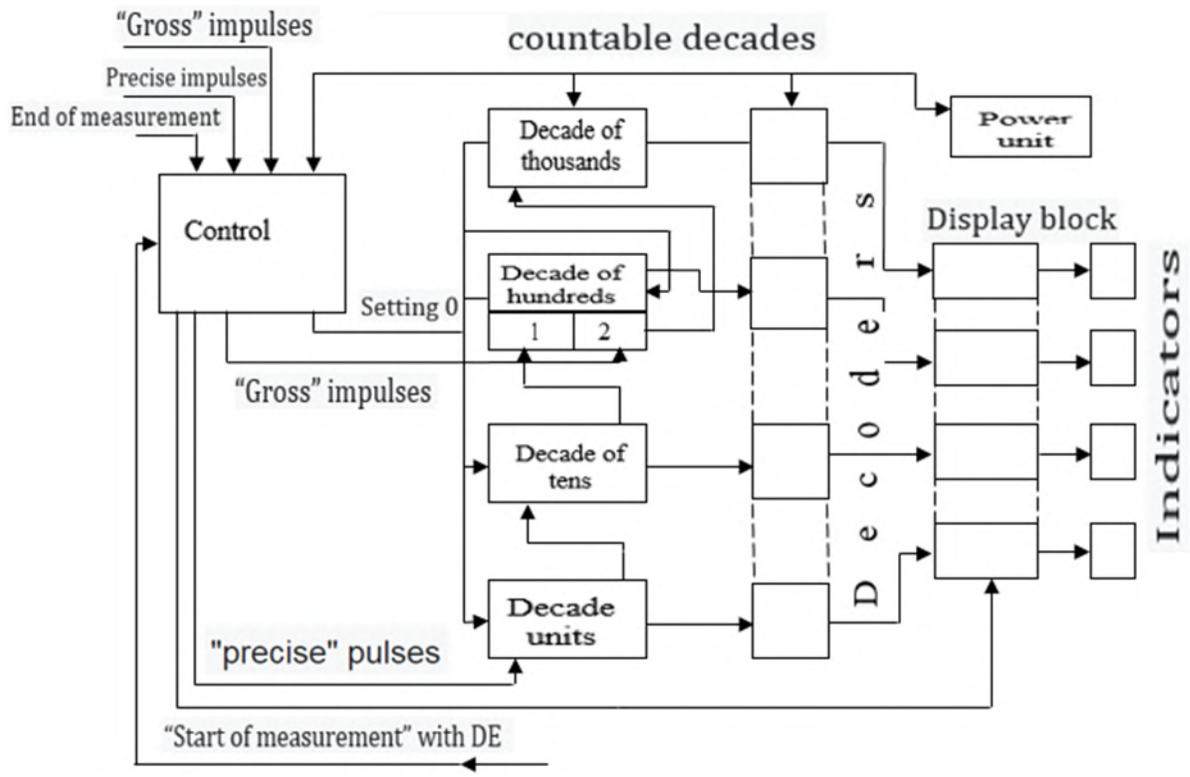

Figure 2. The block diagram of the secondary device.

The device consists of the following blocks: counting decades, decoder, indication, power supply and control.

The block of counting decades is a counter on non-contact triggers and carries out counting of impulses and storing results in the binary number system.

The decoder block, also made on non-contact semiconductor diode elements, decodes the results of the count in the decimal system. The decoded result of the count is transmitted to the display unit, consisting of four identical nodes with luminescent digital indicators (according to the number of decoder matrices), and is marked on it in the form of a four-digit number expressing the reading of the device.

The control unit sends pulses to start and end the measurement.

When compensation is reached, the null-organ turns off the lever motor, the counting of pulses stops.

After the pressure is removed, the discrete and continuous compensation systems return to zero.

With the piezometric method, the weight of the oil product in the tank is determined by the formula

$$G = pF_{av}(H), \tag{3}$$

where p is the hydrostatic pressure of the liquid column in the tank (determined by pulse counting), $F_{av}(H)$ – the average area of the tank at a given filling level H. The value of F_{av} is found from the expression

$$F_{av}(H) = \frac{Vh}{H} = \frac{1}{H}\int_0^H F(h)dh, \tag{4}$$

where $F(h)$ dependence of the tank section on height h. Value $F_{av}(H)$ variable in height and determined by calibration tables.

Thus, to find the weight G oil product with the piezometric method, it is necessary to know the filling height. For this purpose, the tanks must also be equipped with level gauges. However, in this case, the requirements for the accuracy of level gauges are low. Calculation of weight according to the reading of the weighing gauge with correction according to the data of the level gauge is simple and can be reduced to finding the weight according to pre-compiled tables [9].

This counting can be performed automatically by adding a computing device to the display unit that performs the multiplication operation.

To improve operational properties, explosion and fire hazard, as well as to simplify the design, the device measures directly the hydrostatic pressure of the oil product, and to it the air pressure supplied by the hydrostatic pressure transducer.

Thus, the process of measuring moisture content with the device is divided into two stages:

1) obtaining dehydrated oil (standard);
2) comparison of the dielectric constants of dehydrated oil (reference) and oil containing water.

Upon receipt of the standard (dehydrated oil), the investigated oil in the amount of 1 liter is placed in an autoclave and heated to a temperature of 170-180 °C.

The pressure in the autoclave is 7-8 kg/cm^2. Studies have established that this mode achieves the best separation of water and oil without changing its chemical properties.

To speed up the process of preparing the standard, forced cooling of oil in an autoclave is used. To do this, water is passed through a coil located inside the autoclave. Cooled to 38 °C, the oil enters the centrifuge, where the water is finally separated from the oil [10].

3. Conclusion

The article also deals with the design of sensor transducers for measuring various non-electrical quantities, as well as methods and devices for obtaining and processing measurement information.

The use of devices allows you to automate the process of pumping oil and the most important technological parameter – the dynamic level, which is especially important for marginal wells. In the experience, electrical automatic control devices, a variety of designs and schemes of measuring instruments were developed and applied.

Depth parameters of the wells, received the technological parameters of the drilling process and the geometric parameters of the wells. I obtained the greatest possibilities for controlling deep parameters during electric drilling, since the power channel connecting the deep-seated electric motor with surface equipment is at the same time a reliable communication channel for telemetry of deep parameters.

In the technological parameters of the electric drilling process, we obtained: the pressure of the tool on the bottom hole, torque, voltage on the downhole electric motor, the temperature of the clay solution, the temperature of the bottom hole, etc.

In this regard, during electric drilling, it is possible to control a complex of technological and geometric parameters of the drilling process and at the same time perform geophysical surveys of wells.

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References

[1] Abitova G, Beisenbi M and Nikulin V 2011 Complex automation of a technological process on the basis of control systems with a three level structure *2011 IEEE International Systems Conference* pp 34–37 URL https://doi.org/10.1109/SYSCON.2011.5929122

[2] Pogonina A M, Pavlov S A and Andryukhov N M 2022 Investigation of Trailed Equipment of a Machine for Installing Flexible Cable Fencing on Roads Using Intelligent Control Systems and Mathematical Modeling *2022 Intelligent Technologies and Electronic Devices in Vehicle and Road Transport Complex (TIRVED)* pp 1–5 URL https://doi.org/10.1109/TIRVED56496.2022.9965524

[3] Zhou D, Azis N, Yang G, Wang Z D, Jones D, Wells B and Wallwork G M 2012 Examining acceptable Dissolved Gas Analysis level of in-service transformers *2012 International Conference on High Voltage Engineering and Application* pp 612–616 URL https://doi.org/10.1109/ICHVE.2012.6357050

[4] Pragale R and Shipp D D 2017 *IEEE Transactions on Industry Applications* **53**(3) 3175–3181 URL https://doi.org/10.1109/TIA.2016.2608958

[5] Wu X, Li X, Yan H and Feng X 2018 Flash Faults Analysis of Signal Lamp of Circuit Breaker on Affusion Electrical Machinery *2018 IEEE 3rd Advanced Information Technology, Electronic and Automation Control Conference (IAEAC)* pp 2114–2117 URL https://doi.org/10.1109/IAEAC.2018.8577544

[6] Molchanov D and Lavrinovich I 2019 Efficiency of Rock Destruction by a Pulse Generator Based on a Linear Pulse Transformer *2019 IEEE Pulsed Power & Plasma Science (PPPS)* pp 1–4 URL https://doi.org/10.1109/PPPS34859.2019.9009799

[7] Qurbanov R S and Jabiyeva A J 2020 A New Model of Movement of Liquids in Porous Medium *10th International Conference on Theory and Application of Soft Computing, Computing with Words and Perceptions - ICSCCW-2019* ed Aliev R A, Kacprzyk J, Pedrycz W, Jamshidi M, Babanli M B and Sadikoglu F M (Cham: Springer International Publishing) pp 690–696 ISBN 978-3-030-35249-3 URL https://doi.org/10.1007/978-3-030-35249-3_89

[8] Aliyarov R Y, Hasanov A B, Ibrahimli M S, Ismayilova Z E and Jabiyeva A J 2019 Forecasting Oil and Gas Reservoirs Properties Using of Fuzzy-Logic Based Methods *13th International Conference on Theory and Application of Fuzzy Systems and Soft Computing — ICAFS-2018* ed Aliev R A, Kacprzyk J, Pedrycz W, Jamshidi M and Sadikoglu F M (Cham: Springer International Publishing) pp 769–773 ISBN 978-3-030-04164-9 URL https://doi.org/10.1007/978-3-030-04164-9_101

[9] Liu H, Xu C, Wang X and Wang T 2012 Identification of Oil/Gas and water zones in geological logging with Support-vector Machine *2012 IEEE 11th International Conference on Cognitive Informatics and Cognitive Computing* pp 279–282 URL https://doi.org/10.1109/ICCI-CC.2012.6311161

[10] Yao Y and Ji Z 2010 Systematic Evaluation on Sequestration and Driving Effects by CO2 Injection in Reservoir *2010 Asia-Pacific Power and Energy Engineering Conference* pp 1–4 URL https://doi.org/10.1109/APPEEC.2010.5448650

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Research of borehole drilling parameters for determining the optimum size of granite stone blocks

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Research of borehole drilling parameters for determining the optimum size of granite stone blocks

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Abstract. The optimal geometrical parameters of boreholes in dimension stone quarries, whose impact on granite blocks separation and splitting efficiency, are determined, taking into account the stress-deformed state of rock massif. The crack initiation process is analysed considering the flat problem of elasticity theory. Determine destruction parameters of natural stone by borehole methods using the calculations of the required distance between the boreholes in the row along the splitting line with the specified borehole diameters, and created forces of stone destruction are proposed. The optimal shape of splitting block from massif depends on the specific plane of splitting is determined. The possible directions of borehole deviation from ideal ones, their extension due to drilling and tensions in the boreholes are studied. The introduction of the borehole's overlapping coefficient, which influences the weakening of the massif along the directed (designed) split line, is proposed to define further necessary tensions for mechanical ways of separating blocks. The equations for determining drilling operations parameters at granite blocks splitting from dimension stone quarries massifs are proposed. The coefficient of limit values of deviation angles is defined.

1. Introduction

Extraction of natural stone in dimension stone quarries consists of different processes such as: drilling, blasting, splitting, cutting, crushing, excavation, etc. Besides mining, many of those operations also apply to civil engineering [1].

Extraction technology of dimension stones is characterized by specific factors that aim to keep the physical and mechanical natural stone properties and get blocks with a straight shape and effective commercial size [2].

All used methods for dimension stone block extraction can be divided into crack-forming, split-shaping, physical, technical and combined methods. Still, the most common ones are crack-forming and split shaping.

Used split-shaping (fracturing methods) methods for the creation of critical tensions in the splitting planes are formed by drilling boreholes. Fracturing methods into splitting with shims, control blasting processes or thermal procedures and using non-explosive destructive mixtures are divided.

Using the technology of dimension stone extraction during the process of splitting blocks from the massif mostly the splitting methods by shims are used. In practice, due to drilling deformation and borehole deviation, the horizontal projections of the hole's tops and bottoms usually do not be projected one on one. Sometimes boreholes curvature causes the intersection of the next holes in the middle of the length or near their bottoms. In such case, it causes the formation of large rough surfaces after splitting on the block's surfaces, that result in significant losses of stone in further processing operations. The incorrect position of the boreholes' bottom causes the unequal concentration of splitting tensions. It is the result of diagonal fracture formation.

Extraction of natural stone blocks has a large amount of drilling. The quality of drilling operations performance determines the effectiveness of further operations for splitting blocks from the massif. Borehole deviation from the design position causes an increase in the volume of drilling operations due to an increase in the length of drilled boreholes. When using fracture-forming methods, the deflection of borehole axes causes a change in the geometry of splitting forces spreading, affecting the efficiency and quality of the splitting and separation process. Borehole deviation when performing drilling operations of stone massif drilling can cause increased separation area, tool costs, and poor quality of block production. The quality of drilling boreholes is determined by a number of indicators: mode parameters of the drilling process, type and condition of drilling tools, and state of the rock mass. One of the most promising directions of improving extraction processes is optimizing drilling operating parameters, considering the natural fracturing and physical and mechanical properties of dimension stone [3].

Thus, the research of the impact of these factors on the efficiency of drilling operations is a topical scientific and practical task, the solution of which will improve the efficiency of extraction natural stone technology and the quality of natural stone blocks.

2. Statement of the problem

Recently many researchers were based on such important operations as drilling, which was performed with different materials, particularly dimension stones drilling in quarries. Drilling is an important process during dimension stone extraction because an inefficient drilling process can cause huge operational losses [4]. That's why mining enterprises should attempt to optimize those losses. Optimizing drilling losses is also sufficiently effective for further developing mining technologies [5].

Many studies and research for increasing drilling process efficiency are based on determining the optimal speed of penetration of the drill steel (jackrod) and sintered diamond coring a bit into massif. It is based on the optimal choice of the type of drilling equipment according to the current condition of massif and determination of the sufficient force for penetration into the rock [6]. Assessing drilling efficiency considering rocks' properties is also an important part of research [7].

Another scientific and applied drilling problem is the problem of geometric linearity deformation and extension of the boreholes. During drilling, the drill steel and the sintered diamond core bit strike the rock mass, forming a borehole [8]. As a result, a circular borehole wall becomes deformed, and the total borehole area is also changing. This process can cause further crack creation and reduce tensions in the splitting plane [5].

Calculating the optimal tensions for splitting blocks from massif is also important to analyze the micro-cracking process. Particularly this analysis can be found in the following work [9, 10], where are described the micro-cracking process and analysis of mechanical features of rocks during splitting [11]. The crack creation and the process of further formation of cracks are described by Huang et al [12].

The optimization of technological mining parameters in the quarry for dimension stone blocks quality improvement, which is based on photogrammetric measurement techniques, is researched by Levytskyi et al [13].

During extraction of the dimension stone, it is important to study the massif's deformation mode (stress-deformed state) in detail. The boreholes drill along the splitting line of the monolith.

All previous studies do not indicate how much the hole deviation line from the designed direction reduces the coefficient of massif weakening. Also, the problem of the loss stone coefficient changing after the deflection of boreholes is not considered earlier as a result of a change in the shape of stone blocks, causing to increase in the costs of further processing.

3. Methodology

The method of determining the destruction of stone by hole methods is to determine the required distance between boreholes in the line of splitting with given borehole diameters, creating splitting tensions. Throughout the studies, full-scale measurements of lengths and diameters were carried out of boreholes. After the block was splitted off, the azimuths of boreholes deviation from the optimal directions and the dimensions of the directly extracted blocks with all inequalities were considered (figure 1).

Figure 1. Splitted block by hydro shims.

According to this method, it was determined that the optimal shape of the splitted block from the massif (the equality of splitting planes and their mutual perpendicularity) depends on the specific area of splitting, i.e. the correlation of the area formed by the split plane to the total area of splitted block or monolith.

4. Results

The study about the causes of the drilled borehole's deviation shows that it occurs due to geological, technical and technological factors. During the drilling of the borehole, deviations can occur due to the following reasons: encounter with a crack, a stress state factors of the massif, inaccuracies in the installation of the perforator, a clearance due to physical tool wear or structural defects in the particular part of the drilling machine and influence of the surface roughness on which the machine is installed for the accuracy of the installation.

The least studied and the most actual research on borehole drilling is the definition of the influence of the zone of overlapping holes on the deviation of the borehole according to the designed position [14].

The criterion for determining the maximum permissible values of the hole deviation angle from the vertical is the condition of excluding its intersection with the next holes. It should be noted that the limit criterion is valid in such cases when the borehole axis coincides with the plane of borehole lines. In case the difference between the azimuthal borehole axis angle and the plane of borehole lines, the maximum deviation angle will be determined by additional geomechanical determination of the stone blocks splitting process.

In practice, vertically drilled boreholes are over-crossed with one or a series of sub-horizontal cracks. Each of these cracks adds value to the axis deviation angle. For the linear drilling method, the criterion for the quality of drilling is also the geometric parameters, namely the orientation of boreholes that may intersect with each other.

Only for different dimension stones, the method of line drilling, which is combined with the mechanical stresses initiation in the boreholes, the quality of drilling operations will be determined in addition to the geometric parameters, also by parameters of formation of the stone massif tenses. Methods of calculation of the borehole parameters, which are based on practical experience and conducted scientific research, are used in the technology of dimension stone block extraction.

The dimension stone extraction calculation methodology by splitting boreholes method is determined by the required distance between holes within the boreholes line of the given diameter and splitting stone forces.

The research has established that the quality of the stone splitting from the massif (the equality of splitting planes and their mutual perpendicularity) depends on the specific splitting plane. That is the ratio of the area formed by the holes to the overall area of splitted block or the monolith.

One of the important technological parameters of the extraction of granite blocks is the required distance between the holes that are drilled in the designed splitting plane. These formulas were obtained empirically and analytically and provided a diagram of the stress state of the rock monolith, where the static stress acts inside the wells without stress concentrators.

For calculation of the distance between boreholes, it is proposed to use an equation that, when used further, obtains the most accurate results:

$$L = \frac{\pi d_h l_h p(t)}{2H\sigma_p k(t)}, \tag{1}$$

where d_h − diameter of the borehole; l_h − borehole length; $p(t)$ − pressure on the walls of the borehole; H − granite monolith height; σ_p − ultimate rock tensile strength; $p(t)$ − a coefficient that takes into account the reduction of the strength of the stone from the time of loading, which varies from 0,1 to 0,7, depending on the orientation of the splitting plane along the layer, or at an angle to it (anisotropic properties). During the drilling of the borehole line for splitting, in addition to the basic equations of the flat problem of elasticity theory, the plane of borehole displacement from its ideal location has to be considered. It means that the borehole has neither deviation in the azimuthal direction (α), nor in a circular direction (ϕ) (figure 2).

To determine the specific splitting area for one shim, a dependence which takes into account both geometric parameters of splitting and the anisotropic properties of natural stone, which makes it possible to use it in different deposits, was used:

$$S_0 = k_a \left(1 + \frac{PU}{\sigma_p r_g}\right) m^2, \tag{2}$$

where k_a− coefficient defines the anisotropic properties of the rock (for erupting rocks k_a = 0,2−1,0).

For the best splitting stone direction k_a = 1,0, and in the direction $\pi/2$, $3\pi/2$, for labradorite k_a = 0,6, gabbro-norite k_a = 0,2, granite k_a = 0,4; P − pressure in the system, Pa; r_g step between elements of hydro rock splitting systems installation, m; σ_p − tensile strength of granite,

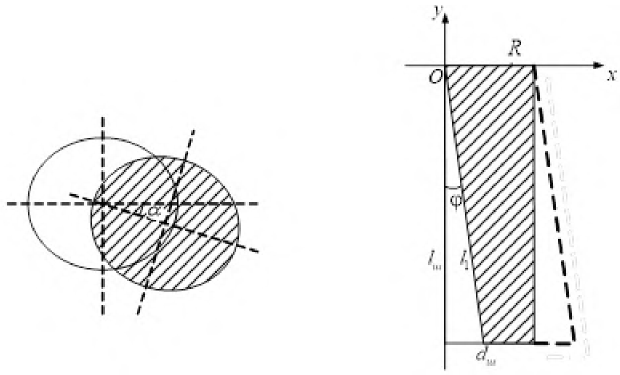

Figure 2. Borehole pattern.

MPa; U − specific relaxation ratio of the splitting plane by drilled boreholes, which depends on the location of the boreholes in the splitting plane:

$$U = \frac{zd_b}{S} = \frac{zd_b}{ah}, \tag{3}$$

where z − total drilled holes length in the splitting plane, m; d_b − diameter of the hole, m; S − the block cut-off area with the length (a) and the height (h), m^2.

The values of z are determined from the dependence:

$$z = (l_{bg}n_{bg} + l_{bp}n_{bp})k_{dr} = \left(\frac{a}{r_g} - 1 + k_n\left(\frac{a}{r_g} - 1\right)\right)hk_{dr}, \tag{4}$$

where l_{bg}, l_{bg} - length of boreholes where there are hydro rock splitting systems installed $(l_{bg} = h)$ and additional boreholes for massif weakening $(l_{bp} = k_n)$, m; n_p, n_{bp} – number of boreholes respectively for the installation of hydro rock splitting systems and additional boreholes for massif weakening; k_{dr} − uneven rate of drilling $(k_{dr} = 0,9)$; r_p − distance between additional boreholes for massif weakening, m; k_n − coefficient of reducing the length of weakening holes $(k_n = 0 - 1)$.

Reducing the above expressions and also taking into account that splitting is performed in the vertical plane of the dimension stone blocks with the length a and height h for $l_{bg} = h$ and $l_{bp} = h/3$, we obtain the following relation (correlation):

$$S_0 = k_a\left(1 - \frac{P(3r_p + r_g - 4r_gr_p)k_{dr}d_b}{3\sigma_pr_g^2r_p}\right), \tag{5}$$

As it seens from the expression, the specific splitting area by hydro rock splitting systems does not depend on the height h of the ledge.

The technological coefficient of losses from the drill-split shim method of separating granite blocks k_{tl} is determined by the following equation:

$$k_{tl} = \frac{\pi d_b^2 z}{4abh}. \tag{6}$$

An ideal borehole area and an actual overlapping area are introduced. The ideal borehole area can be described by equation $S_i = l_nd_n$. The actual overlapping area can be described by equation $S_n = f(l_h; d_h; \alpha\phi)$

The coefficient of splitting plane weakening: $K_{alap} = \frac{S_i}{S_h}$.

In the limit values at the maximum deviation, the coefficient of massif weakening will be for $\alpha = 0^0 - S_h = \pi R \frac{l_n}{\cos\phi}$, for $\alpha = 90^0 - S_h = \frac{\pi R}{2} l_2 = \frac{\pi R^2}{2\sin\phi}$. So in all other possible positions, the actual boreholes overlapping area will be:

$$S_h = \left[\frac{\int_0^3 (l_h; d_i; \phi) d\phi}{\int_0^{90} (l_h; d_i; \alpha) d\alpha}, \right. \tag{7}$$

Taking to according that the loss coefficient and the weakening massif coefficient depend on such parameters as hole diameter and depth, which in most cases equals the height of the bench. It can be argued that when splitting the block, it is also necessary to take into account the split-line direction if the designed directions of drilling operations are not kept.

As a result of field measurements, experimental values of the reduction of the weakening massif coefficient were obtained due to the deviation of holes from the designed direction. As a result, the values of the weakening coefficient were determined for different values of the directional angle and the vertical deviation angle; the graphic representation of this dependence is shown in figure 3.

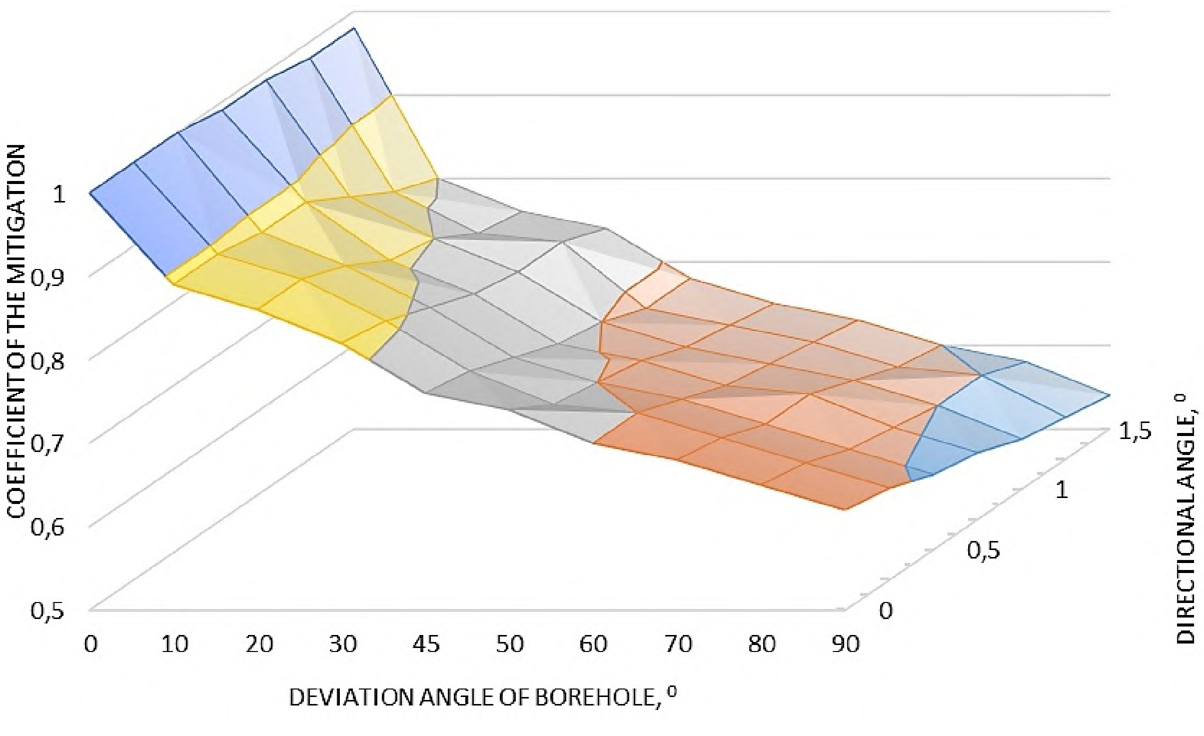

Figure 3. Change the coefficient of the massif mitigation.

The above formula of technological loss coefficients, Eq. (7), allows you to determine the coefficient of removal of blocks and the complex productivity of equipment for preparing blocks for extraction.

In an ideal three-dimensional model of massif cracking, the geological coefficient of loss kg.l = 0, since the main systems of cracks are parallel with each other and their planes intersect at right angles. Separate this three-dimensional model on the SQL, SQS, SSL planes, the simple models of individual location crack systems location in the dimension stone massif we obtained (figure 4).

Considering the absence of ideal conditions on natural stone deposits, a non-orthogonal model was introduced in which the basic systems of cracks do not intersect at a right angle γ. At the

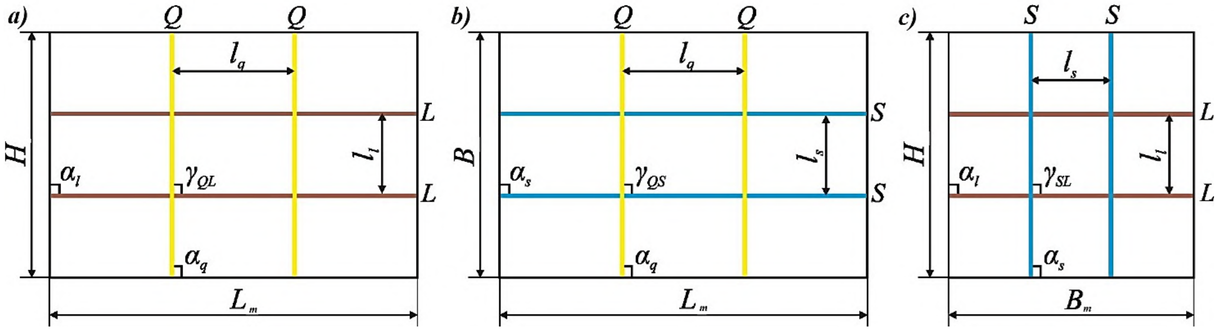

Figure 4. Orthogonal models of the propagation of Q_{LS} systems in the natural stone massif: a) the longitudinal vertical plane of S_{QL}; b) the blanket horizontal plane S_{QS}; c) the lateral vertical plane of S_{SL}.

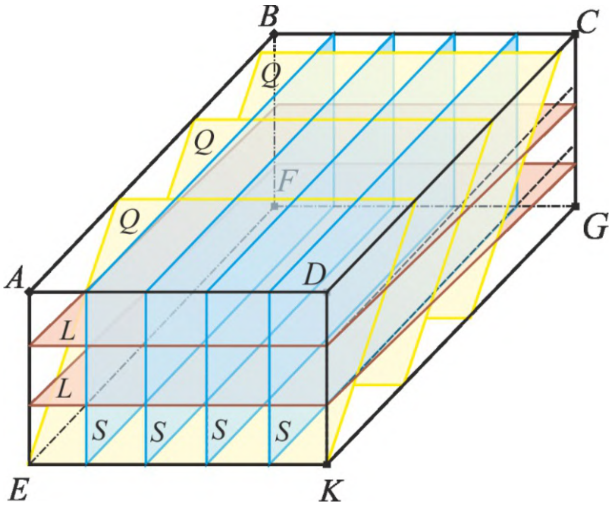

Figure 5. Three-dimensional model of a natural stone massif fracture.

same time, it is considered that the angles of falling cracks in the massif are constant; that is, all the cracks of one system are parallel. Given all the above, a three-dimensional model of the fracture of an array (figure 5) was developed, which will allow determining the most optimal directions of drilling operations with the subsequent minimal losses of minerals.

The following dependencies determine areas of separation planes in the case with:

$$S_m^{QL} = L_m H_m = \frac{1}{\sin\gamma_{QL}}\left[\frac{(n_l l_l)^2 \sin\alpha_q \cos\alpha_q}{\sin\gamma_{QL}} + n_l n_q l_l l_q\right]; \tag{8}$$

$$S_m^{QS} = L_m B_m = \frac{(n_q l_q \sin\gamma_{QS} + 0,5 n_l l_l \sin 2\alpha_q)(n_s l_s \sin\gamma_{QS} + 0,5 n_i l_i \sin 2\alpha_s)}{\sin\gamma_{QS}^2 \sin\alpha_q \sin\alpha_s}; \tag{9}$$

$$S_m^{SL} = B_m H_m = \frac{1}{\sin\gamma_{SL}}\left[\frac{(n_l l_l)^2 \sin\alpha_s \cos\alpha_s}{\sin\gamma_{SL}} + n_l n_s l_l l_s\right]. \tag{10}$$

where H_m, L_m, B_m – height, length and width of the monolith, respectively, m; n_q, n_s, n_l – amount of blocks between planes respectively of transverse Q, longitudinal S and smooth L cracks of the massif, within the linear dimensions of the monolith, units; l_q, l_s, l_l – distance between the planes of the corresponding systems of cracks, m; α_q, α_s, α_l – falling angles of the corresponding cracks systems, degrees; γ_{QL}, γ_{QS}, γ_{SL} – angles between the corresponding cracks systems that determine the non-orthogonally of the cracks systems with each other, degrees.

The indicator, which characterizes the overall geometric parameter of breaking, is the specific plane of splitting. In mining practice, the line of drilled holes in a certain vertical plane, due to some deviation of their axis, will only partially intersect the designed plane. Only in the case of a deviation of the hole along the planned plane of splitting its section throughout its length will it keep in this plane.

5. Conclusion

The value of the specific splitting area during the monolith preparation to the extraction will be less than the estimated, which effect to splitting parameters of blocks from the dimension stone massif. Therefore, the overall quality index of drilling can be taken as a performance criterion for splitting blocks from the massif.

The values of tensions allow analysing the conditions for the creation of cracks for splitting blocks from the dimension stone massif. It should be borne in mind that the theory of failure considers only the most significant stresses, not taking into account that other present stresses also affect the achievement of the critical state. The critical value is σ_γ for a dimension stone massif. It can be determined the critical tension initiates cracking formation.

The quality of the stone preparation for splitting depends first of all on the plane of designed split plane, the main characteristic of which is the specific value of splitting plane. As proved by the calculations, this value depends on the angle of borehole inclination. It was researched that boreholes have different values of deviations from vertical, which cause a decrease of the specific value of splitting plane, which depends on the azimuthal α and the zenith angles ϕ of hole axis along the designed split-line. It is obtained that the most negative values of the azimuthal angle α are observed in the range from 72° to 90°, and the zenith angle ϕ from 0,75° to 1,4°.

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References

[1] Epiroc Middle East FZE 2023 Dimension Stone Industry | Uses and Applications | Epiroc URL https://www.epiroc.com/en-qa/applications/construction/quarrying-and-surface-construction/dimension-stone-industry

[2] Yarahmadi R, Bagherpour R, Taherian S G and Sousa L M O 2019 *Bulletin of Engineering Geology and the Environment* **78**(1) 533–542 ISSN 1435-9537 URL https://doi.org/10.1007/s10064-017-1040-5

[3] Miyazaki K, Ohno T and Karasawa H 2018 Effects of Rock Properties on Bit Wear in Percussion Drilling of Granite (*ISRM International Symposium - Asian Rock Mechanics Symposium* vol All Days) pp ISRM–ARMS10–2018–210 URL https://onepetro.org/ISRMARMS/proceedings-pdf/ARMS1018/All-ARMS1018/ISRM-ARMS10-2018-210/1184732/isrm-arms10-2018-210.pdf

[4] Bilim N and Karakaya E 2021 *Mining, Metallurgy & Exploration* **38**(1) 359–366 ISSN 2524-3470 URL https://doi.org/10.1007/s42461-020-00322-6

[5] Van Viet P, Anh Tuan N and Van Hoa P 2020 *Inżynieria Mineralna* **1**(2) 95–103 URL https://doi.org/10.29227/IM-2020-02-13

[6] Abbas N, Li K, Abbas N, Ali A, Ali M and Hussain J 2022 *Scientific Mining Journal* **61**(4) 185–191

[7] Zhang Z X, Gong F, Kozlovskaya E and Aladejare A 2023 *Rock Mechanics and Rock Engineering* **56**(4) 3139–3158 ISSN 1434-453X URL https://doi.org/10.1007/s00603-023-03216-3

[8] Wang J, Hu Y, Liu Z, Li L, Liu B and Huang L 2021 *Shock and Vibration* **2021** 8813984 URL https://doi.org/10.1155/2021/8813984

[9] Servet D, Nazmi S, Ibrahim U, Tamer E, Deniz A and Rasit A 2014 *International Journal of Mining Science and Technology* **24**(2) 269–273 ISSN 2095-2686 URL https://doi.org/10.1016/j.ijmst.2014.01.020

[10] Fattahi H and Bayat N 2020 *Geotechnical and Geological Engineering* **38**(5) 5693–5693 ISSN 1573-1529 URL https://doi.org/10.1007/s10706-019-00971-5
[11] He Y, Han L, Zhang H and Liu H 2016 *Chinese Journal of Rock Mechanics and Engineering* **35**(1) 16–22
[12] Huang Y H, Yang S Q and Tian W L 2019 *Fatigue & Fracture of Engineering Materials & Structures* **42**(6) 1341–1356 URL https://doi.org/10.1111/ffe.12990
[13] Sobolevskyi R 2014 *Proceedings of the Mining Institute named after D.A. Kunaeva* (1) 259–266
[14] Levytskyi V, Makhno A, Panasiuk A and Mamrai V 2018 *"The Journal of Zhytomyr State Technological University" / Engineering* (2(82)) 259–267 URL https://doi.org/10.26642/tn-2018-2(82)-259-267

Improving the system for ensuring the safety of workers in the mining industry on the basis of risk management

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Improving the system for ensuring the safety of workers in the mining industry on the basis of risk management

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Abstract. The unfavorable situation that has developed in the economy due to the war in Ukraine, the difficult working conditions of workers in the mining industry, the lack of efficiency of labor protection measures taken lead to an increase in the level of occupational morbidity among employees of enterprises. The need for safety requires the setting of tasks, within which it is necessary to conduct a detailed analysis of a specific production activity, identify its inherent dangers and develop effective measures to protect the personnel. The purpose of the work is to develop a system of events for improving the level of safety in the mining industry on the basis of risk management, which will reduce the dynamics of occupational diseases at work. The importance of the work is in the implementation of a systematic analysis of the harmful production factors impact, taking into account working conditions, the intensity and duration of these factors impact on miners throughout their work experience in order to prevent, timely diagnose, and treat patients with occupational diseases. The introduction of methods and techniques to improve the level of safety at mining enterprises will ensure a decrease in the level of occupational morbidity among workers.

1. Introduction

Along with difficult mining and geological conditions, the level of accidents, injuries and occupational diseases is significantly affected by the crisis in the coal industry of Ukraine in terms of technical, economic, financial and social indicators. As of the beginning of the year, there are 148 mines in Ukraine, 102 of which are state-owned. Most of the mines are located in the territory not controlled by Ukraine (67), 2 more mines are not operating, 33 are operating (but only 4 are considered profitable). That is, about 30 mines are modern enterprises, and more than half of the mines operate without reconstruction, have complex ventilation networks and multi-stage underground transport. In the total fleet of operating downhole equipment, the share of mechanized mining complexes and road headers of a new technical level is only 2%. In general, the industrial and production assets of coal mining enterprises are worn out by an average of 65% [1].

The main reason for the crisis state of the industry is insufficient funding, when the volume of capital investments, which has decreased by more than 3 times, and the prices of materials and equipment have increased 2, 3 and more times. Low salary levels and delays in their payment have become the main reason for the outflow of qualified personnel [2]. In this connection, in the indicated crisis conditions, the role and tasks of the labor protection management system operating in the coal industry increases (the main goal of which is to create safe and healthy working conditions in accordance with the requirements of labor safety rules) [3].

High rates of occupational morbidity in the mining industry and insufficient efficiency of the measures taken for labor protection satisfy neither the owners, nor employees, nor the state. The dynamics of occupational morbidity indicators is evidence of the absence of trends in its decline, and the share of workers in the mining industry accounts for about 76% of diseases [4]. Solving the problem, a significant reduction in the level of occupational morbidity of workers at coal enterprises, is an urgent and priority task. The most vulnerable link in the current approaches to the prevention of occupational diseases was the lack of 1) a regulatory and methodological framework for calculating risks, building work regimes, 2) methods of stimulating economic interest in carrying out activities through the system of compulsory social insurance, 3) conducting in-depth medical examinations of miners and social rehabilitation measures [5]. In this regard, it is necessary to develop new conceptual approaches to the prevention of occupational diseases of workers of coal enterprises, based on the development of methodological principles for managing the risk of occupational diseases in coal mines, which make it possible to increase the effectiveness of preventive measures.

The aim of the work is to develop methodological principles for managing the risk of occupational diseases at mining enterprises, which make it possible to increase the efficiency of the occupational health and safety management system and measures to prevent occupational diseases of workers. The main idea of the work is to identify harmful production factors, based on the analysis of working conditions for the entire length of service of an employee of the coal industry. And also the formation of methods for the prevention of occupational diseases, based on the principles of taking into account risk factors for the development of occupational diseases, and establishing the dependence of their manifestation in order to predict (predict) a possible occupational disease. Development and implementation of measures to reduce the level of occupational morbidity of workers who work at mining enterprises.

The object of the research is the occupational health and safety management system and the prevention of occupational diseases of workers who work at mining enterprises.

Research objectives: analysis of the state of occupational morbidity in the coal industry and the regulatory legal framework for the investigation and registration of cases of occupational diseases; identification of indicators of the significance of harmful production factors; to establish the etiology and causation of occupational diseases at typical workplaces of workers in an underground group of coal mines; establishment of patterns of development of occupational diseases depending on specific working conditions (tension, severity) and development of risk management methods; development of a set of indicators for assessing the effectiveness of the functioning of the labor protection management system to reduce the risk of occupational diseases and the classification of working conditions and occupational diseases development of an algorithm for managing the risk of occupational diseases for workers who work at mining enterprises; development of methodological principles for managing the risk of occupational diseases, development of an algorithm and mechanism for transforming the existing system for the prevention of occupational diseases at mining enterprises.

The coal industry is considered one of the most dangerous sectors of the economy. Working conditions in coal mines are characterized by a number of factors that have a harmful effect on the human body. Harmful factors include rock dust, noise, vibration, sudden temperature changes, high air humidity, the need to work in a forced position, and harmful gases. The impact of these factors causes occupational diseases of workers and the number of occupational diseases in the coal industry is increasing.

In the structure of occupational morbidity of workers in the mining industry, the largest specific weight is made up of diseases of dust etiology, musculoskeletal system and vibration diseases. In industry, most of the industrial production personnel work at elevated levels of dust content – 58.4%, noise – 55.7%, vibration – 28.5%, chemical factors – 14.5%, humidity – 14.9% and temperatures that do not meet sanitary standards – 15.0% [6]. Figure 1 shows the structure by production factors that caused occupational diseases.

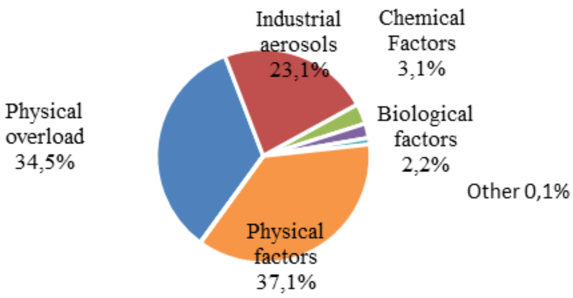

Figure 1. Distribution of harmful and hazardous production factors causing occupational diseases in coal mines.

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High levels of indicators of the severity of the labor process (classes 3.1 – 3.3) are observed in working specialties and mid-level specialists. In the first group, high rates are due, first of all, to the lifting and movement of excess cargo masses by hand, forced tilts of the body at an angle of more than 30 and movements in space. In the second group, the need to use in the process of work a large number of portable control measuring instruments, which are used directly by the employee, and movements in space due to the technological process. High indicators of the severity of the labor process are a prerequisite for the development of diseases of the musculoskeletal system. High indicators of the intensity of the labor process are directly related to the specific conditions of underground work, which requires knowledge of a series of instructions both on labor protection and industrial safety, and on mining, and, in addition, with high emotional stress.

To assess the risks of occupational diseases, it is necessary to use effective methods of their identification, based on taking into account all hazardous and harmful production factors with the use of express methods for assessing the intensity and severity of the labor process, the Map of the working conditions of workers, as well as establishing the causal relationships of certain forms of diseases from exposure complex of harmful and dangerous production factors [7].

2. Results and discussion

As a result of research and application of mathematical methods of analysis, the regularities of the risk of occurrence of certain types of occupational diseases in workers were identified and presented, depending on the profession and work experience [8]. In the study, the risk of getting an occupational disease for workers in a certain profession is understood as the probability of an employee getting sick in relation to the total number of workers in reduced working conditions. Risk is calculated using the following formula (1):

$$R = \frac{N_d}{N}, \tag{1}$$

where N_d – number of workers with occupational diseases in a particular profession; N – total number of workers.

The processing of data on occupational diseases made it possible to obtain data on the risks of diseases for the main underground professions, depending on the length of service in hazardous working conditions (table 1).

Table 1. Risks of getting occupational diseases in mines.

Profession	The risk of occupational disease Work experience in adverse conditions, years					
	10-14	15-19	20-24	25-29	30-34	35-39
Tunneller	0.0012	0.0112	0.031	0.0410	0.0454	0.0462
Longwall miner	0.0010	0.0123	0.0291	0.0423	0.0491	0.0512
The operator of mining excavation machines (in the longwall)	0.0005	0.0121	0.0318	0.0407	0.0495	0.0497
Underground miner	–	0.0007	0.0041	0.0047	0.007	0.0081
Underground electrician	0.0004	0,0025	0.0053	0.0071	0.0072	0.0080
Mining master	–	0.0024	0.0087	0.0105	0.0132	0.0147
Mining assembly worker	–	0.0017	0.0026	0.0035	–	–

The results obtained make it possible to predict the occurrence of an occupational disease in workers, depending on the length of service at the enterprise. For this purpose, data on identified occupational diseases at more than 10 coal enterprises from 2015 to 2021 were used, taking into account the total number of workers employed in production. The resulting cumulative dependencies between these parameters are shown in figure 2.

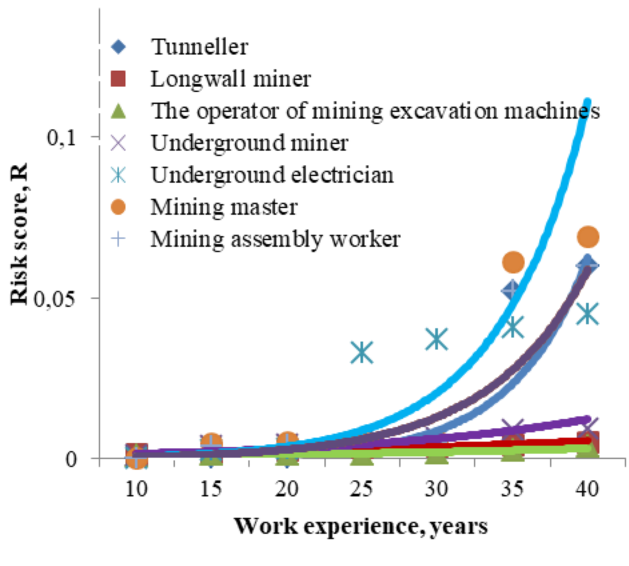

Figure 2. Cumulative dependence of occupational disease on the length of service in professions in coal mines.

Estimated data are described with the greatest accuracy by a dependence of the form (2):

$$y = a \cdot e^{bx}, \tag{2}$$

where y – an indicator of the risk of getting an occupational disease; x – work experience; a, b – regression coefficients.

The values of the coefficients a and b are presented in table 2.

Table 2. Values of indicators of the dependence of occupational disease on the length of service in professions in coal mines.

Profession	Coefficient values		Correlation	Student's coefficients	
	a	b	relationship	calculated	tabular
Tunneller	0.0009	0.1231	0.85	12.81	2.02
Longwall miner	0.0006	0.1381	0.85	11.95	2.02
The operator of mining excavation machines (in the longwall)	0.0003	0.1571	0.82	10.82	2.02
Underground miner	0.00001	0.1871	0.73	8.75	2.02
Underground electrician	0.0003	0.0991	0.86	13.02	2.02
Mining master	0.000009	0.2362	0.78	9.53	2.02
Mining assembly worker	0.00001	0.1815	0.72	8.75	2.02

The analysis of cases of occupational diseases in more than 10 enterprises made it possible to establish the critical period of work experience in the profession, in which the largest number of cases is observed.

For all professions, when assessing absolute values, it was 20-24 years. The decrease in the number of cases of occupational diseases after 20-24 years of professional activity of an employee is statistically due to the fact that the number of employees with a total length of service (in the total number of employees) is removed in connection with the release of a preferential pension and with an established occupational disease in earlier years of employment [9].

The obtained results of the study make it possible to develop diagnostic maps for assessing the risk of an occupational disease depending on the length of service, degree and type of exposure to harmful and dangerous working conditions on an employee in the main professions – longwall miner, drifter, operator of mining excavation machines (in the longwall), underground miner, mining foreman, underground electrician, miner (table 3).

Table 3: Diagnostic card for assessing the risk of occupational disease in longwall miners, depending on the length of service and diagnosis in coal mines.

Types of occupational diseases	Work experience, years						
	10-14	15-19	20-24	25-29	30-34	35-39	total (for all years)
Polyneuropathy (vegetative-sensory) of the upper limbs from functional overexertion	0.00020	0.00060	0.00040	0.00030	0.00030	0.00000	0.00179
Vibration disease from exposure to local and general vibration	0.00060	0.00417	0.00447	0.00358	0.00179	0.00089	0.01551

Continuation of table 3

Types of occupational diseases	Work experience, years						
	10-14	15-19	20-24	25-29	30-34	35-39	total (for all years)
Sensorineural hearing loss, bilateral with systematic exposure to occupational noise	0.00030	0.00209	0.00298	0.00298	0.00119	0.00030	0.00984
Shoulder periarthrosis (adhesive shoulder capsulitis, shoulder periaotritis, "frozen shoulder")	0.00000	0.00030	0.00060	0.00000	0.00000	0.00000	0.00089
Professional bronchitis	0.00020	0.00040	0.00149	0.00060	0.00060	0.00030	0.00358
Bursitis of the elbow joint	0.00000	0.00060	0.00119	0.00060	0.00000	0.00000	0.00239
Pneumoconiosis caused by dust containing silicon dioxide: silicosis, anthracosilis, asbestosis, talcosis and others	0.00000	0.00030	0.00060	0.00119	0.00000	0.00000	0.00209
Lumbosacral radiculopathy from functional overexertion	0.00030	0.00119	0.00209	0.00298	0.00149	0.00000	0.00805
Lumbosacral muscular-tonic syndrome from functional overexertion	0.00000	0.00089	0.00119	0.00060	0.00030	0.00000	0.00298
Dust bronchitis, non-obstructive	0.00010	0.00060	0.00050	0.00040	0.00020	0.00000	0.00179
Radiculomyelopathy of the lumbosacral region from functional overexertion	0.00000	0.00000	0.00030	0.00089	0.00000	0.00000	0.00119
Radiculomyelopathy of the cervical spine from functional overexertion	0.00000	0.00010	0.00020	0.00000	0.00000	0.00000	0.00030

Continuation of table 3

Types of occupational diseases	Work experience, years						
	10-14	15-19	20-24	25-29	30-34	35-39	total (for all years)
Chronic obstructive (asthmatic) bronchitis	0.00010	0.00050	0.00060	0.00089	0.00078	0.00010	0.00298
Compression mononeuropathies of the lower extremities from functional overexertion	0.00000	0.00010	0.00020	0.00000	0.00000	0.00000	0.00030
Cervico-shoulder radiculopathy from functional overexertion	0.00000	0.00010	0.00050	0.00000	0.00000	0.00000	0.00060
Compression mononeuropathies of the upper extremities from functional overexertion	0.00000	0.00000	0.00010	0.00000	0.00030	0.00020	0.00119
Total	0.00149	0.01193	0.01700	0.01491	0.00775	0.00239	0.05547

– Minimal risk
– Acceptable risk
– Unacceptable risk

Thus, the revealed patterns of the risk of certain types of occupational diseases among workers, depending on the profession and work experience, are a sufficient and necessary basis for developing methodological principles for managing the risk of occupational diseases [10].

The paper developed methodological principles for managing the risk of occupational diseases at mining enterprises, proposed a coefficient of working conditions, according to which the classification of enterprises was carried out depending on the likelihood of exposure to harmful and dangerous production factors on workers. An algorithm for managing the risk of occupational diseases and approaches to improve the functioning of the labor protection management system in the field of reducing the risk of occupational diseases have also been developed.

The minimum risk of occupational diseases is understood as the value of the risk probability in the first class of the probationary exposure of the diagnostic card for assessing the risk of an occupational disease in which the disease is recorded.

The unacceptable risk of an occupational disease is understood as the maximum value of the risk probability according to the diagnostic chart for assessing the risk of an occupational disease [11].

The acceptable risk of an occupational disease is understood as the value of the probability of the risk of an occupational disease, which is between the minimum and maximum risk of a diagnostic chart for assessing the risk of an occupational disease.

The results obtained made it possible to identify the patterns of occurrence of occupational diseases among workers, depending on the length of service, profession, degree and type of exposure to harmful and dangerous working conditions, and also to develop an algorithm for managing the risk of occupational diseases [12].

Thus, taking into account risk factors (profession, length of service in hazardous conditions, type of exposure to harmful and dangerous production factors) of the occurrence of an occupational disease and establishing a dose-related dependence of the occurrence of a certain type of occupational disease in a particular profession, allows you to predict a possible occupational disease and redistribute the quality and level of control over working conditions and health of the staff [13].

The regional system of labor protection should have in its arsenal a set of effective management methods, the control over the work of which, as an object of management, includes mining enterprises that differ in natural, technical, technological and organizational conditions [14].

At present, classifications are widely used according to one attribute (and usually the most important), which determines the general level of danger of the mine and the technological principles of coal mining (methane content, gas emission) [15].

At the present level of development of the science of labor protection, it is possible to develop multidimensional classifications according to the factors that determine the level of danger to the health of workers [16]. This makes it possible to single out indicators of enterprise groups that are increasingly stable in terms of variability, which is a way to more accurately determine the rationality of applying certain methods of managing these objects [17].

Currently, most researchers prove that the probability of the implementation of occupational diseases should be considered as a set of random variables [18]. This circumstance, as well as the selective nature of the information used, determines the feasibility of a probabilistic-statistical approach to the classification of mining enterprises.

The main stages of the proposed methodology for classifying by the level of risk of occupational diseases are:

- the choice of parameters by which the object is delimited;
- formation of a training sample;
- choice of object delimitation method;
- establishing the homogeneity of the selected object.

One of the main tasks in the classification of objects is the choice of parameters by which the existing sample is distinguished into homogeneous groups. Studies have shown that working conditions are assessed by a fairly wide range of indicators [19].

The working conditions at the mine with a sufficient degree of objectivity can be characterized by the following indicators: tension, severity, harmful substances, microclimate, illumination, infrasound, vibration, noise.

Also in the work, a mechanism for improving the labor protection management system in coal mines, the results of testing the developed methods and proposed principles, as well as an assessment of the effectiveness of the proposed measures to improve the labor protection system are given. The study of the regularity of the occurrence of occupational diseases in coal mines made it possible to establish that they vary within a fairly wide range and their nomenclature is also different [20].

Theoretical and practical interest is to identify the relationship between working conditions in mines and occupational diseases [21].

To do this, it is advisable to introduce the concept of specific occupational morbidity M_s (the risk of getting an occupational disease), the value of which is calculated by the formula (3).

$$M_s = \frac{M_{gen}}{N}, \tag{3}$$

where M_{gen} – is the general morbidity at the mine; N – is the number of employees at the mine.

The sample of occupational diseases was formed according to the data of 10 mines. The resulting relationship between M_s and C_{work} (working conditions coefficient) shown in figure 3.

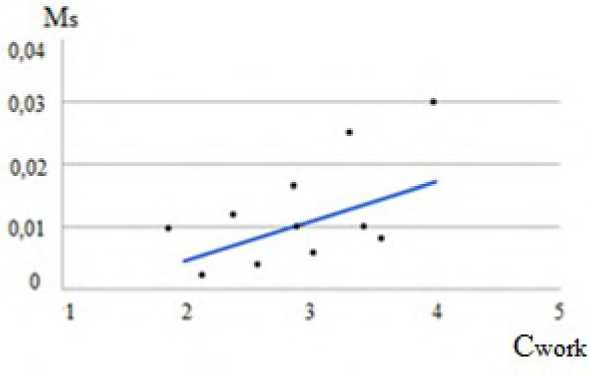

Figure 3. Dependence of the coefficient of working conditions and the value of specific occupational morbidity in coal mines.

The resulting dependence is most accurately described by the following formula of the form (4).

$$M_s = 0.2168e^{0.302C_{work}}. \quad (4)$$

The correlation ratio is 0.67, and the coefficient of determination is 0.45. This means that 55% of the occurrence of an occupational disease is explained by other factors.

One of these factors is the effectiveness of the functioning of the labor protection management system at mines. Thus, in order to characterize the level of efficiency of the functioning of the labor protection management system of an enterprise in terms of managing the risks of occupational diseases, it is proposed to use the efficiency coefficient of the labor protection management system (5).

$$C_e = \frac{C_{work}}{M_s}. \quad (5)$$

According to the value of this coefficient, 3 groups of coal mines can be distinguished:

- mines with an effective labor protection management system (C_e>300);
- mines with an inefficient labor protection management system (C_e<10);
- mines with an inefficient labor protection management system (10<C_e<300).

The conducted studies allowed to formulate methodological principles for managing the risk of occupational diseases in coal mines.

To manage the risk of occupational diseases based on taking into account long-term dependencies, predict possible occupational diseases and redistribute the quality and level of control over working conditions and health of personnel, it is necessary to adhere to such principles. This is a coordinated interaction of the key subjects of the coal mine – the owner of the capital, management, personnel, state supervision and control bodies. Ensuring the necessary and sufficient level of prevention of occupational diseases. Monitoring of risk factors for occupational diseases, including observation, assessment, control and forecast of the state of the working environment, equipment, technology and production organization. Purposeful formation of an information base of risk factors for occupational diseases and mechanisms of their development. Improvement of rehabilitation mechanisms and development of medical and social rehabilitation infrastructure. When using methods such as assessment of working conditions, assessment of the risk of occupational diseases, assessment of the effectiveness of the functioning of the labor protection management system, classification of coal mines according to working conditions and occupational diseases. assessment of the risk of an occupational disease depending on the profession, work experience in hazardous conditions and diagnosis, prediction of possible occupational diseases, assessment of the effectiveness of preventive measures [22].

Especially important is the choice of the way to change the labor protection management system – it is revolutionary, evolutionary and corrective. The revolutionary way of changing the labor protection system involves a radical change in the structure of the system, its functions, organization of activities, methods, methods and means of control. The evolutionary way does not require a fundamental change in the existing structure, but its functions must be reviewed. The corrective path is aimed at constantly maintaining a high level of efficiency of the existing system, searching for reserves and resources of the system in order to reduce costs and form an additional fund of funds for the prevention of occupational diseases of coal mine workers. To select the optimal management solution for the transformation of the labor protection management system, it is proposed to distinguish the effectiveness of its work into three levels (table 4).

Table 4. Choice of management decisions to improve the labor protection system.

Level efficiency labor protection management systems	Meaning efficiency ratio (C_e)	Required changes	Conversion Methods labor protection management systems	Necessary actions to move to a higher level of efficiency of the labor protection management system
High	C_e>300	Permanent corrective	Development of programs, research works, methods	Assessing the risks of occupational diseases, monitoring the state and potential the current labor protection management system
Middle	10<C_e<300	Evolutionary	Analysis and modification of the functions of the labor protection management system	
Low	C_e<10	Revolutionary (cardinal)	Analysis and change in the structure of the labor protection management system, formation of a new labor protection management system	

3. Conclusions

The high level of occupational morbidity among miners is due to the low efficiency of the functioning of the labor protection management system in coal mines, the increase of which requires a radical change in the methodology of its formation, transformation, adjustment and improvement.

The results of the investigation of cases of occupational morbidity indicate the insufficient effectiveness of their prevention. This is due, first of all, to the fact that the labor protection management system of enterprises is not aimed at preventing and preventing occupational diseases, but in fact at fixing them. The current systems are based on the concept of implementing a secondary prevention program, that is, carrying out measures to restore already significantly impaired physiological functions of the body under the influence of production activities.

To identify dangerous and harmful factors and assess the risks of occupational diseases, express methods have been developed and proposed for assessing the intensity and severity of the labor process, indicators of the significance of the main harmful and dangerous production factors.

Taking into account the risk factors for the occurrence of an occupational disease, which makes it possible to establish a time dependence of the occurrence of a certain type of occupational disease in a particular profession, makes it possible to predict a possible occupational disease and redistribute the quality and level of control over working conditions and the health of personnel.

To implement the principle of differentiated management of labor protection, it is proposed to classify mines according to working conditions and occupational diseases. The most effective method of such classifications is the method of principal components.

Necessary and sufficient conditions for the development and implementation of methodological principles for managing the risk of occupational diseases in coal mines and, on this basis, improving and developing the labor protection management system of enterprises are application of the principles of prevention of occupational diseases, based on the consideration of risk factors for the development of occupational diseases, the application of patterns of development of occupational diseases; depending on the specific working conditions (tension, severity), the use of a set of methods and criteria for assessing the effectiveness of the functioning of the labor protection management system, in terms of prevention occupational diseases; application of an algorithm for choosing the optimal set of preventive measures to reduce the risk of occupational diseases while maintaining the material well-being of the employee.

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References

[1] Tubis A, Werbiska-Wojciechowska S and Wroblewski A 2020 *Applied Sciences* **10**(15) 5172 ISSN 2076-3417 URL https://doi.org/10.3390/app10155172
[2] Matloob S, Li Y and Khan K Z 2021 *Open Journal of Business and Management* **9**(3) 1198–1209 URL https://doi.org/10.4236/ojbm.2021.93064
[3] Yang L, Birhane G E, Zhu J and Geng J 2021 *Frontiers in Public Health* **9** ISSN 2296-2565 URL https://doi.org/10.3389/fpubh.2021.709987
[4] Cortes-Ramirez J, Naish S, Sly P D and Jagals P 2018 *BMC Public Health* **18**(1) 721 ISSN 1471-2458 URL https://doi.org/10.1186/s12889-018-5505-7

[5] Verma S and Chaudhari S 2016 *International Journal of Mining Science and Technology* **26**(4) 691–702 ISSN 2095-2686 URL https://doi.org/10.1016/j.ijmst.2016.05.023
[6] Ribalta C, Viana M, López-Lilao A, Estupiñá S, Minguillón M C, Mendoza J, Díaz J, Dahmann D and Monfort E 2018 *Annals of Work Exposures and Health* **63**(1) 107–123 ISSN 2398-7308 URL https://doi.org/10.1093/annweh/wxy092
[7] Hebblewhite B Geotechnical risk in mining methods and practice: critical issues and pitfalls of risk management *MGR 2019: Proceedings of the First International Conference on Mining Geomechanical Risk* ed Wesseloo J (Australian Centre for Geomechanics) pp 299–308 URL https://doi.org/10.36487/ACG_rep/1905_17_Hebblewhite
[8] Yevtushenko N, Ponomarenko O, Tverdokhliebova N, Mezentseva I, Semenov Y and Yevtushenko S 2022 *Metal and Casting of Ukraine* **30**(3(330)) 117–125 URL https://doi.org/10.15407/steelcast2022.03.116
[9] Piosová M, Andrejiova M, Badida M and Moravec M 2021 *International Journal of Environmental Research and Public Health* **18**(11) 5910 ISSN 1660-4601 URL https://doi.org/10.3390/ijerph18115910
[10] Bochkovskyi A 2020 *Journal of Scientific Papers "Social Development and Security"* **10**(3) 93–103 URL https://doi.org/10.33445/sds.2020.10.3.8
[11] Katz J and Pietrobelli C 2018 *Resources Policy* **58** 11–20 ISSN 0301-4207 Special Issue on Mining Value Chains, Innovation and Learning URL https://doi.org/10.1016/j.resourpol.2018.02.001
[12] Vlachos T 2018 Certifiable Risk Management & Business Continuity Approach in Mining Industry *Proceedings of the 4th World Congress on Mechanical, Chemical, and Material Engineering (MCM'18) (Madrid, Spain)* p MMME 108 URL https://doi.org/10.11159/mmme18.108
[13] Ionica A and Edelhauser E 2007 *Fascicle of Management and Technological Engineering* **V(XV)** 1941–1946 URL https://mpra.ub.uni-muenchen.de/9588/
[14] Yevtushenko N, Tverdokhliebova N and Mezentseva I 2022 *Educational Challenges* **27**(2) 228–241 URL https://doi.org/10.34142/2709-7986.2022.27.2.16
[15] Donovan S L, Salmon P M, Lenné M G and Horberry T 2017 *Ergonomics* **60**(10) 1336–1350 URL https://doi.org/10.1080/00140139.2017.1308562
[16] Krzemie A, Suárez Sánchez A, Riesgo Fernández P, Zimmermann K and González Coto F 2016 *Journal of Cleaner Production* **139** 1044–1056 ISSN 0959-6526 URL https://doi.org/10.1016/j.jclepro.2016.08.149
[17] Ponomarenko O, Yevtushenko N, Berladir K, Zapolovskyi M, Krmela J, Krmelová V and Artyukhov A 2022 *Polymers* **14**(9) 1883 ISSN 2073-4360 URL https://doi.org/10.3390/polym14091883
[18] Bbu G B, Moraru R I and Bbu M C 2011 Developing a More Effective Risk Management Process in the Restructured Romanian Mining *International Multidisciplinary Scientific GeoConference: SGEM* vol 1 (Sofia: Surveying Geology & Mining Ecology Management) pp 767–774 URL https://www.proquest.com/openview/5727bed3ddb7ba3c6fc1c192f9894cda/1?pq-origsite=gscholar&cbl=1536338
[19] Nowak-Senderowska D and Patyk M 2021 *Inynieria Mineralna* **1**(2) URL https://doi.org/10.29227/IM-2021-02-57
[20] Spanidis P M, Roumpos C and Pavloudakis F 2021 *Sustainability* **13**(4) 2369 ISSN 2071-1050 URL https://doi.org/10.3390/su13042369
[21] Han S, Chen H, Harvey M A, Stemn E and Cliff D 2018 *International Journal of Environmental Research and Public Health* **15**(11) 2565 ISSN 1660-4601 URL https://doi.org/10.3390/ijerph15112565
[22] Andersen A D, Marìn A and Simensen E O 2018 *Innovation and Development* **8**(1) 1–27 URL https://doi.org/10.1080/2157930X.2018.1439293

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Integrated research into the stress-strain state anomalies, formed and developed in the mass under conditions of high advance velocities of stope faces

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Integrated research into the stress-strain state anomalies, formed and developed in the mass under conditions of high advance velocities of stope faces

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Abstract. This paper studies the ways of solving the resource-saving direction of the strategy for the mining industry development in Ukraine. The existing ideas about the patterns of changing stress-strain state (SSS) in the mass during the stope mining of minerals are analyzed. The problem of the host rock SSS formation and development is studied. The main directions of studying the relationship between the parameters of mass SSS anomalies in the area of stope operations and their technological parameters has been substantiated with the selection of a methodology for conducting multivariate computational experiments. A macromodel has been constructed to calculate the change in the distribution fields of the rock mass SSS components with subsequent substantiation of its idealizations. The principles of matching the macromodel and the subordinate models have been studied. A new methodical approach is proposed for taking into account the time technological parameters (average daily face advance velocity and the duration of its stoppage) through their relationship with the mechanical characteristics of the rocks. A test assessment of the adequacy of the performed calculations based on the spatial model SSS analysis for all stress components has been conducted. The degree of influence of the stope face advance velocity and the mass texture on the parameters of rock pressure anomalies has been studied, as well as the linking patterns in the area of conducting stope operations have been obtained: frontal and lateral bearing pressure zones and a zone of destressing behind the stope face. A base has been created for studying and predicting the rock pressure manifestations in critical areas in order to develop recommendations for choosing rational technological and design parameters for high-rate mining of coal seams.

1. Introduction

At present, the strategy for the development of the Ukrainian coal industry should be aimed at ensuring high-rate mining and, consequently, the use of high-performance stope equipment. In this regard, the problem of effective supporting of mine workings in the zone of stope operations influence, as well as their reuse, becomes relevant. A comprehensive solution to this issue provides a resource-saving focus on mining operations.

The patterns of changes in the coal-bearing mass state as the stope face approaches and retreats have been studied for many decades. Thus, certain ideas [1–5] about the parameters of

SSS anomalies depending on the mining-geological and mining-technical conditions for mining coal seams have been developed by now. There is no doubt that there are three main zones of the anomalous state of the coal-bearing mass around the stope workings and associated with them extraction drifts:

- frontal bearing pressure zone ahead of the face, where the vertical stress σ_y concentration is several times higher than the initial state of the undisturbed rock mass $\sigma_y = \gamma H$ (here σ_y – vertical stresses; H – mining depth; γ – weight-average unit specific gravity of coal-overlaying formation);
- zone of lateral bearing pressure that occurs in the side of the extraction drifts from the side of undisturbed rock mass; here, also, the vertical stress σ_y concentration is several times higher than the initial undisturbed rock mass state;
- destressing zone behind the stope face, which occurs when a cavity is formed after coal mining, into which the roof rock layers are lowered and then collapse; in this zone, vertical stresses can almost completely disappear ($\sigma_y = 0$) near the stope face, and as it retreats, the collapsed rocks are compacted and the rock pressure increases with stabilization at a certain distance at the level of the initial undisturbed rock mass state.

The parameters of the specified SSS rock mass anomalies usually include two interrelated indicators: the value of vertical stress concentrations $K_y = \gamma H$ and the distance of their propagation in the plane of coal seam bedding. Index "i" denotes a family of concentrations K_y (y is the vertical coordinate of the mass) of different values, which quite naturally propagate to different distances l_y.

The noted parameters depend on the mining-geological indicators of mining the coal seams, as indicated by numerous studies, for example, [6–14] in different periods of the coal mining industry development both in Ukraine and in other countries. Among the influencing mining-geological factors (in addition to the mining depth) are, first of all, the mass texture, taking into account the existing discontinuity and the mechanical characteristics of the rock layers at a distance of at least 20 m to the roof and bottom from the seam [15]. One of the main patterns of formation of anomalous SSS zones is considered to be determined, the essence of which is as follows:

- the occurrence in the roof of more thick (from 3 – 5 m and more) and increased hardness (hardness coefficient according to Protodyakonov scale is $f \geq$ 5–6) rock layers increases the propagation l_{y_i} of frontal and lateral bearing pressure zones with a simultaneous increase in vertical stress concentrations K_y near stope faces and in the side of the extraction drift from the side of the undisturbed rock mass;
- the same parameters of lithotypes occurring in the seam roof contribute to a deeper destressing of the mass above the stope face and behind it – the distance l_{y_i} of almost complete destressing ($\sigma_y = 0$) increases, as well as the length of the rock pressure stabilization area at the level of the undisturbed rock mass initial state;
- various types of discontinuity in the roof rocks (fracturing, small-amplitude breaks) act in the opposite direction of influence: the zones of frontal and lateral bearing pressure reduce their propagation in the bedding plane, and the vertical stress concentrations decrease; in the destressing zone, the length of areas of minimum rock pressure propagation, as well as the length of areas of rock pressure stabilization are reduced;
- more thin-bedded and less strong rock layers of the roof cause tendencies similar to the action of various types of their discontinuity.

The noted tendencies for the same region or even the mine field flank are clearly manifested when measuring in the extraction drifts such indirect indicators as the convergence value of the roof and the bottom rocks in the mine working, as well as in its sides. As an example, figure 1 shows graphs (constructed based on the results of measurements) of changes in the drift contour displacements as the stope face advances for two roof rock textures: predominantly thick-bedded and medium-bedded; predominantly thin-bedded and medium-bedded. Moreover, the measurements were carried out in the same driven entry of the seam C_6, Stepova Mine of PJSC DTEK Pavlohradvuhillya, where both types of roof rock textures are present in the length of the extraction site. As it can be seen from the graphs, with a thick-bedded texture, the frontal bearing pressure zone extends ahead of the stope face up to $a_1 = -73$ m in terms of the convergence of roof and bottom rocks $U_{R,B}$ and up to $C_{12} = -73$ m in terms of the convergence of the drift sides U_s. In the area of predominantly thin-bedded and medium-bedded texture of the roof rocks, the length of the frontal bearing pressure zone is significantly reduced: $a_2 = -33$ m (by 2.21 times) $C_2 = -47$ m (by 1.55 times). A similar situation is behind the stope face with regard to the stabilization distance of rock pressure manifestations. Thus, with a predominantly thick-bedded and medium-bedded texture of the roof rocks, the length of the area in terms of the parameter $U_{R,B}$ is 104 m, in terms of the parameter U_s, the distance increases to $d_1 = 124$ m. In the area (in length of the mine working) with a predominantly thin-bedded and medium-bedded texture, these indicators are reduced: $b_1 = 36$ m (by 2.89 times); $d_1 = 72$ (by 1.72 times).

These patterns are typical for various mining-geological conditions and Donbass regions [16–21]; therefore, they should be considered as sufficiently objective and taken into account in further studies.

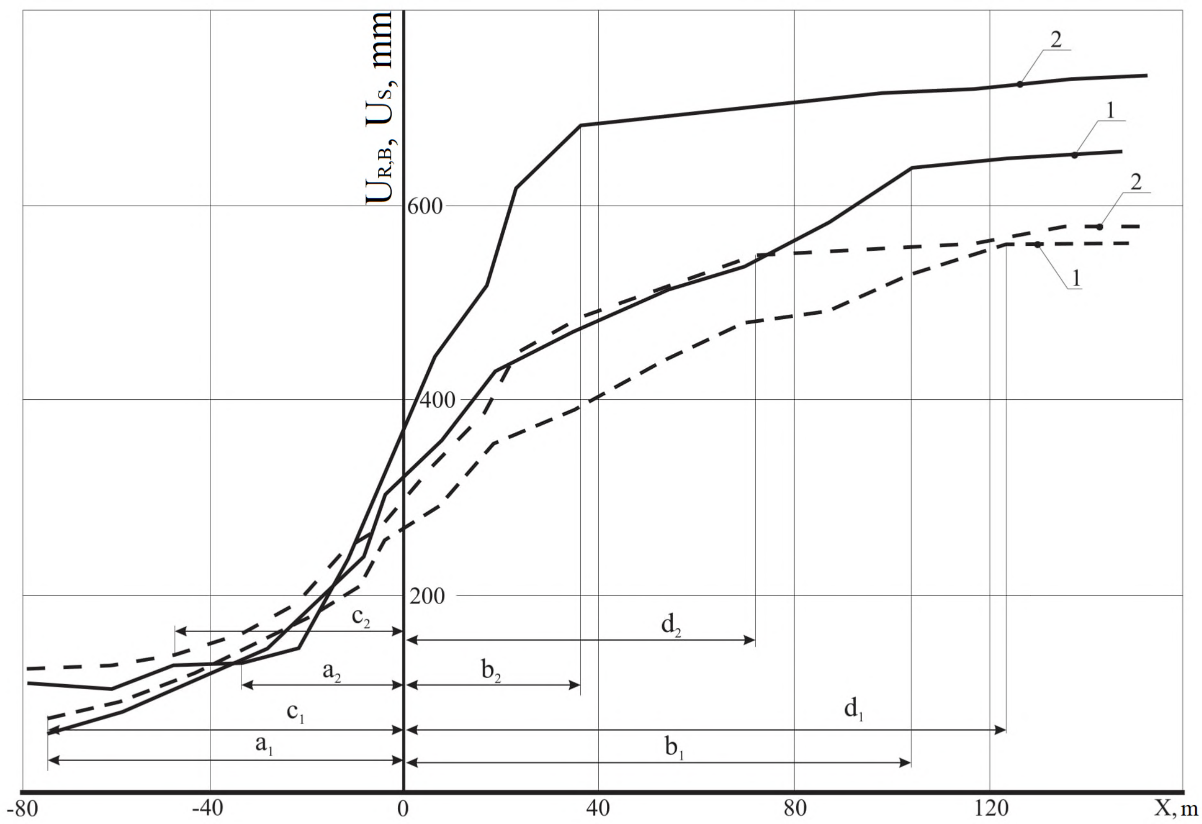


Figure 1. Dependences of the convergence development in the roof and bottom rocks sides of the drift with predominantly thick-bedded and medium-bedded (1), with predominantly thin-bedded and medium-bedded (2) texture of the roof rocks.

Among the variety of technological factors, two are distinguished [22–26], which combine a significant influence, on the one hand, and, on the other hand, are amenable to regulation in the process of stope operations: the average daily velocity V_d of the stope face advance and the duration t of its stoppage.

Thus, the presence of a significant influence of technological parameters (the velocity V_d of the stope face advance and the duration t of its stoppage) of mining the coal seam on the formation of the load on the powered support sections of the stope complex has been experimentally confirmed. The load itself is inextricably linked with the parameters of the SSS anomalies around the stope face, and for this reason, it can be concluded that there is interrelation between the distribution curves of the stress components in the vicinity of the stope face and the specified technological parameters of the coal seam mining. Determining the linking patterns in a numerical form is quite a difficult task due to the influence of many different factors. But, the relevance of studying this problem is undeniable: after all, the experimental results in the Western Donbass convincingly prove a decrease in the rock pressure manifestations by 23 – 47 per cent only due to a change in the velocity of the stope face advance, and this decrease increases the safety of mining operations and equipment life, thereby reducing the probability of accidents.

To date, two main ways have been formed to study the interrelation between the parameters of mass SSS anomalies in the area of stope operations and their technological parameters:

- full-scale experiments for measuring indirect rock pressure indicators and their analysis in order to determine the linking patterns;
- analytical research with the predominant use of numerical methods is the so-called computational experiment.

In this regard, many researchers use a combination of the above methods, for example, [27–29] which is justified by the desire to obtain more reliable results. Undoubtedly, the parameters of SSS anomalies and indicators of rock pressure manifestations are interrelated, and the nature of these relationships is revealed by a set of ideas about the mechanism of a coal-bearing mass displacement in the area of mining operations.

Thus, it seems the most appropriate way to solve the problem of studying the formation and development of SSS anomalies in the mass, which is substantiated by a three-stage structural-logical scheme: mine instrumental observations of the rock pressure manifestations in stope faces and extraction drifts; computational experiments to calculate the surrounding mass SSS and a linking element – the mechanism of rock displacements in the coal-overlaying formation, revealing the influence of the stope face advance velocity and the duration of its stoppage.

2. Substantiating the methodology for conducting multivariate computational experiments

To date, rich experience has been accumulated in measuring the indicators of rock pressure manifestations in various mining-geological conditions [30–32].

The main attention is paid to the substantiation of the methodology for modeling different velocities V_d of the stope face advance as the primary stage; further, the results of the mass SSS calculations are analyzed in conjunction with the parameter V_d and the patterns of its influence on the indicators of rock pressure anomalies in the vicinity of the stope face are determined.

When substantiating the methodology for conducting a computational experiment, we had to face a number of factors, the objective reflection of which in geomechanical models is conditioned by significant difficulties.

Firstly, the model of a stratified rock mass with two conjugated mine workings located in it (stope face and an extraction drift) is characterized, in addition to its extensive dimensions in space (figure 2), by a combination of significant heterogeneity of the geometric, mechanical and strength parameters of the elements that constitute this model. Thus, only the model of one rock mass includes a sufficiently large number of rock layers of the roof and bottom in the coal seam, differing from each other in mechanical properties. The strength characteristics of contacts of adjacent lithotypes for the Western Donbass conditions [33–35], as a rule, are very low, or there is no adhesion along the bedding planes at all. In addition, the research object is located in the zone of active influence of stope operations, where, along with significant vertical displacements of the coal-bearing mass, significant movements occur in the horizontal direction of the rock layers relative to each other.

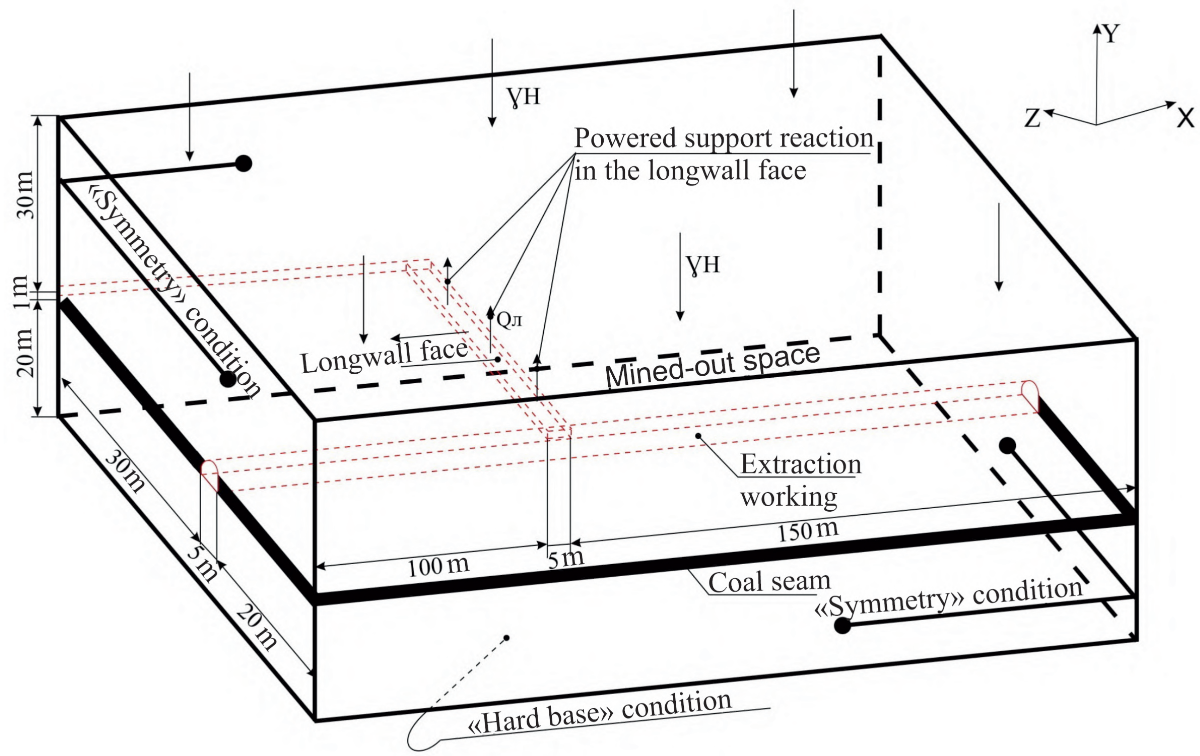


Figure 2. Macromodel for studying rock pressure anomalies in the area of stope operations.

The noted facts make it possible to predict the destruction of contacts between adjacent rock layers, and this leads to a significant change in the distribution fields of the rock mass SSS components [36]. In addition to these factors, it is also necessary to take into account the processes of weakening the rock layers (occurrence of tension cracks, partitioning into blocks and their partial caving into the mined-out space). More intense fracturing [37] and the occurrence of the so-called thrust-block systems in the roof increases their deformation capacity for more significant displacements, and rocks caved into the mined-out space radically change their mechanical characteristics [38–40]. These factors have been sufficiently tested using modern methodologies for modeling geomechanical processes [41, 42].

Secondly, it is necessary to more adequately and reliably represent the real mining-technical conditions of mining operations and to model in detail the objects for supporting mine workings (support of a stope face and extraction working, security structure, etc.) in accordance with their design and technological peculiarities. Each of these objects includes a set of elements with complex geometry, significant heterogeneity of mechanical properties and strength parameters. In this case, one of the main difficulties is the ratio of the scales of object elements and the rock mass texture parameters (the difference reaches two or three orders of magnitude), which is a serious obstacle to the stable conduct of a computational experiment.

Similar problems of the available degree of modeling idealization relate to the mechanized hydroficated support of a stope face. Undoubtedly, from the point of view of the reliability and adequacy of the research, it will be positive to reflect the actual design of the powered roof support used in a particular calculation, in accordance with its technical characteristics. However, when developing such a detailed model, it is necessary to overcome (for a long period of time) serious difficulties when reflecting the real operation modes of hydraulic prop stays and hydraulic cylinders, as well as hinged joints of the section elements. At the same time, a significant computing resource is required to calculate the SSS of only one powered roof support section, and in the stope plow set, for example, there are 196 such sections.

Thirdly, when taking into account the time factor (the stope face advance velocity and the duration of its stoppage), it is necessary to use an appropriate physical model (for example, viscoplastic) of the rock mass behavior (primarily) in combination with special technological methods (for example, regular changes in the parameters of the final element mesh) of a computational experiment [43,44]. This formulation of the problem is not only time-consuming, but also requires significant computing resources in the absence of guaranteed calculation process stability.

As a result of the analysis of three groups of factors influencing the computational experiment reliability, an opinion has been formed on the need to introduce a number of idealizations and simplifications into the geomechanical model, which would have a minimal effect on the adequacy and accuracy of the final SSS calculation results, but at the same time significantly save the computing resource.

The approach described above is associated, first of all, with the consistent implementation of interrelated studies, the essence of which is the division of tasks and their consistent solution by constructing a common macromodel and more detailed development of subordinate models. The methodology for performing phased studies is as follows.

The macromodel dimensions are indicated on the scheme and determined based on: previous experience in modeling geomechanical processes in similar mining-geological conditions; experimental studies of rock pressure manifestations in the extraction drifts of the Western Donbass mines; normative guidance documents.

Thus, the methodological approach in terms of the phased and continuity of research provides a reasonable construction of two groups of subordinate models with a high degree of detailing the fastening and security elements of extraction workings. The adequacy of the reflection implies modeling of real parameters: frame support of the TSYS series; roof-bolting system combined of resin-grouted rockbolts and rope bolts; security structure (behind the stope face); the central and side prop stays of the strengthening support.

When constructing subordinate models at the second stage of research, the following methodological approach has been developed.

Firstly, to ensure the stability of the SSS calculation, it has been decided to switch to flat models that reflect the section in the plane YZ, that is, the cross-section of the extraction working. The accumulated experience of calculating such models proves the high reliability of conducting the computational experiment.

Secondly, in the absence of a real possibility of a detailed reflection of the scheme elements for supporting an extraction working (in a spatial model) of considerable length, the two most critical areas of the drift has been selected, for each of which its own group of flat models is constructed:

- the first area is a zone of frontal bearing pressure at a distance of $3 - 5$ m from the stope face, where the maximum concentrations of vertical and other stress components act, provoking an active increase in the load on the fastening structure;

- the second area is the zone of stabilization of rock pressure manifestations behind the stope face, where the main part of the drift contour displacements has already been realized (figure 1), that is, the load approaching the maximum has been formed.

Thirdly, instead of the geomechanical system spatial construction in the critical areas of the drift, a set of flat models is proposed, each of which reflects the extraction working section (with a model thickness equal to a step of frame setting) with different supporting elements. The above is explained in figure 3 and figure 4, where one of the most effective schemes implemented in the Western Donbass mines is used as an example. The scheme for fastening and supporting extraction workings includes:

- in the area of frontal bearing pressure zone: a frame support made of special profile SCP-27 of the TSYS series, set with a step of 0.8 m; resin-grouted rockbolts placed symmetrically in each side of the mine working in the middle of the inter-frame space with a step of 0.8 m; rope bolts, set in a checkerboard pattern in length of the mine working in the middle of the inter-frame space with a step of 3.2 m (every four frames) according to the scheme in figure 3; central and side wooden prop stays of strengthening support, placed with a step of 0.8 m;
- additional fastening elements are set behind the stope face to support the drift for its reuse: side wooden prop stays of strengthening support are set continuously along the mine working and include two rows; there is one breaker-prop row on the drift berm.

The construction of three drift sections in each of the selected areas makes it possible to track changes in the SSS along the mine working in order to determine the degree of loading of fastening elements and identify their most dangerous sections.

Fourthly, in order to bring the loading conditions of flat models into conformity with the coal-bearing mass state, determined during the calculation of the macromodel, the following actions are performed. For the area with the maximum frontal bearing pressure (3 – 5 m ahead of the stope face plane), three flat models are constructed (figure 3), in which the dimensions (in the plane YZ), structure and boundary conditions completely coincide with those for the macromodel. The results of calculating the vertical stress σ_y distribution curve for a flat model and a macromodel are compared. As an object of comparison, the contact plane of the immediate and main roof of the seam are chosen, which is conditioned by the greatest influence of the rocks in this area (immediate roof and one or two layers of the main roof) on the state of the extraction working fastening elements. Next, an external load (geostatic pressure) is selected at the flat model upper boundary, at which the distribution curves σ_y have a minimum difference from each other, which contributes to a more adequate reflection (within the framework of a flat model) of the coal-bearing mass behavior in real three-dimensional measurement (macromodel). Similar actions are performed for flat models in the zone of stabilization of the coal-overlaying formation displacements.

Thus, the two-stage research makes it possible to determine two groups of patterns of the influence of the stope face advance velocity on the parameters of rock pressure anomalies near the stope face and the SSS of fastening elements of modern schemes for supporting extraction workings intended for repeated use. The analysis of these patterns is of significant practical value in the conditions of highly loaded stope faces.

To conduct a series of computational experiments for studying the influence of the stope face advance velocity V_d, an interval of 5 m/day $\leq V_d \leq$ 15 m/day is chosen, which most fully reflects both the mine conditions of coal mining using the previous generation of stope equipment, and the modern performance achieved using the equipment of latest generation. Three discrete values of the average daily velocity of the stope face advance (V_d = 5 m/day, 10 m/day and 15 m/day) are selected, for each of which a separate computational experiment is performed.

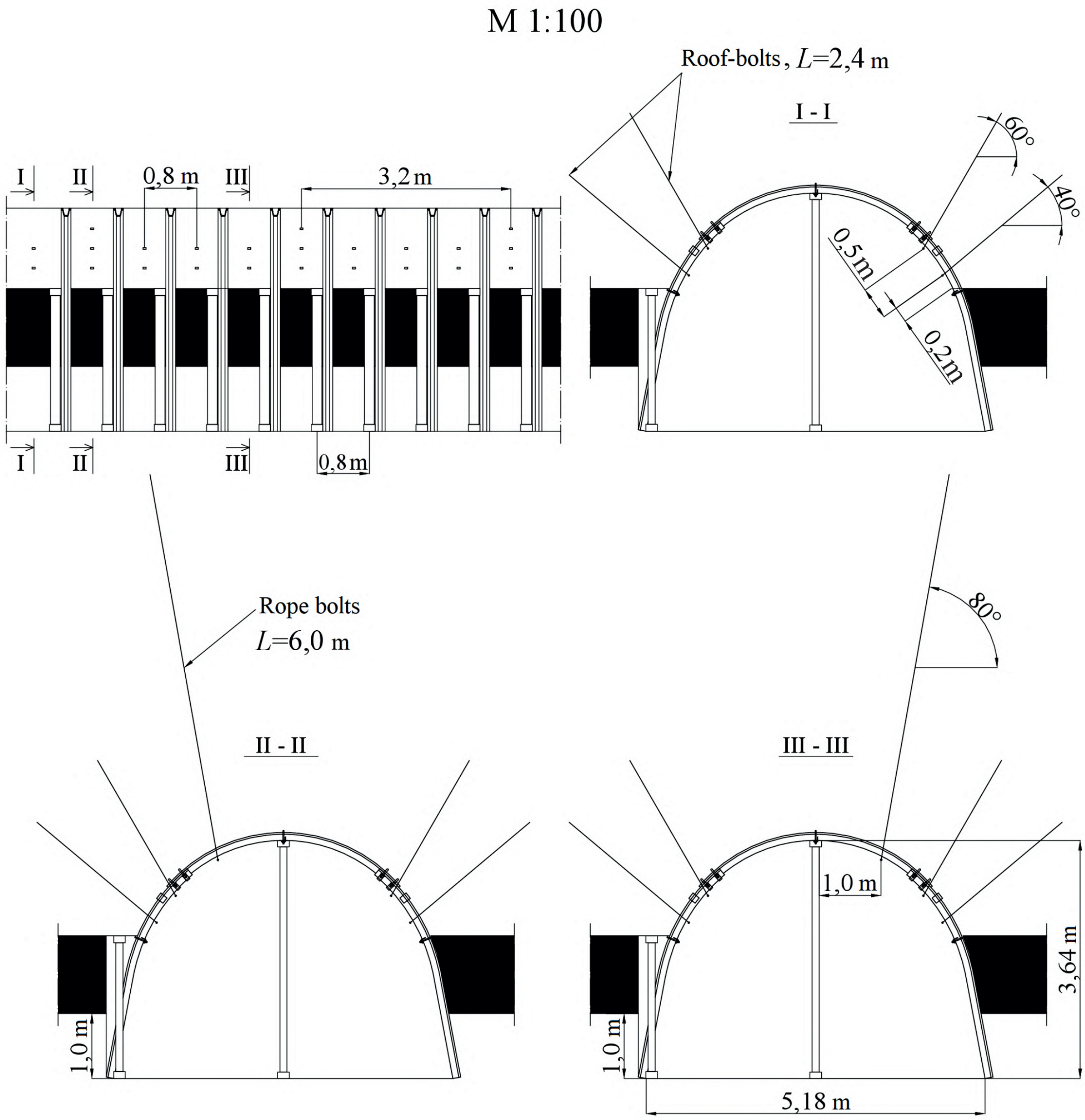


Figure 3. Scheme for fastening the extraction working in the frontal bearing pressure zone.

Within the framework of the second idealization, a methodology has been developed for "linking" all three values of V_d to the deformation modulus of each of the lithotypes included in the macromodel.

In modern computer programs, in particular ANSYS, the development of creep deformations ϵ_{creep} is usually represented in the form

$$\varepsilon_{creep} = C_1 \sigma^{C_2} t^{C_3} \tag{1}$$

where C_1, C_2, C_3 – approximation coefficients of experimental creep diagrams in the coordinates "deformation ε – loading time t"; σ – stress intensity; t – time of loading the rock samples.

Equation (1), along with a sufficient simplicity of written form, most objectively reflects the rheological process of the creep deformation development, since it uses the results of experimental

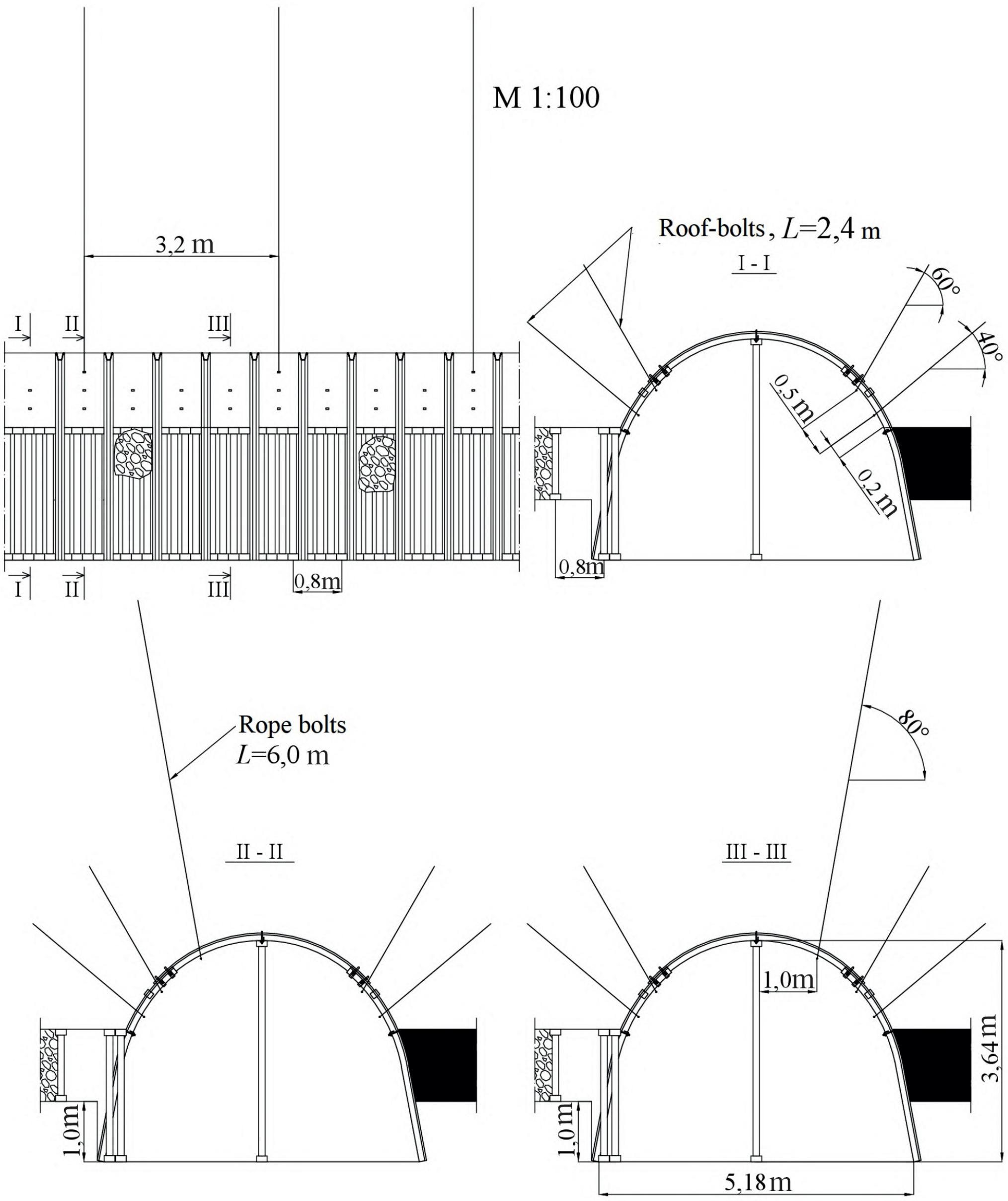


Figure 4. Scheme for supporting the extraction working in the displacement stabilization zone of the coal-overlaying formation behind the stope face.

studies accumulated to date. In this regard, one of the tasks is to match the parameters of the experimental diagrams “deformation – loading time” as reliably and adequately as possible with the parameters and coefficients included in equation (1).

3. Substantiation and studying the stress-strain state of “mass – support” geomechanical models

For a complete and adequate study of the process of formed rock pressure anomalies, the mass spatial model has dimensions (x = 255 m, z = 55 m, y = 50 m), which completely exclude the influence of boundary conditions and “edge” effects on its faces.

Based on the existing information provided by the geological surveys of the Western Donbass mines (stratified mass of weak rocks), the most common textural variants of the coal-bearing stratum are summarized and two types of its texture are formed: predominantly thin-bedded and medium-bedded; predominantly thick-bedded and medium-bedded. These two textural types are shown in figure 5 and accepted for research in order to determine patterns of influence on the parameters of rock pressure anomalies.

The data of geological surveys of mines, studies of M.S. Polyakov Institute of Geotechnical Mechanics NAS of Ukraine and a number of studies [18, 19], on the mechanical properties of the coal-bearing stratum; average characteristics for each lithotype are introduced into the geomechanical model.

The orientation in space of the stope face and the extraction working associated with it is fully reflected, taking into account the formation of bearing pressure and destressing zones.

The real parameters of the latest technology for supporting extraction workings have been modeled.

The developed algorithm of methodical methods makes it possible to assess the influence of the stope face advance velocity on the stress-strain state of the coal-bearing mass, the fastening and security structures of the extraction workings.

4. General analysis of the SSS of spatial models

Then, the assessment of rock pressure anomalies is studied that occur in the rock mass in the area of stope operations from the point of view of the correspondence of the computational experiment results for a spatial geomechanical model to existing ideas about the processes of coal-bearing rock mass displacements. Thus, the term “general SSS analysis” refers to a certain test assessment of the adequacy of the performed calculations.

The spatial model SSS analysis is carried out for all stress components, and the most informative ones are distinguished to illustrate the distribution curves: vertical stresses σ_y, horizontal stresses σ_z (along the extraction site) and stress intensity σ.

For the test analysis, fragments of the SSS calculation of one of the computational experiments (predominantly thick-bedded and medium-bedded mass with a relatively moderate stope face advance velocity of 5 m/day) are selected, since the general tendencies are qualitatively the same for other computational experiments with other initial data.

An analysis of the vertical stress distribution in the spatial model (figure 6, b) presents the following results.

Firstly, on the one hand, the spatial model clearly reflects all the main rock pressure anomalies in the vicinity of the stope: frontal and lateral bearing pressure zones; destressing zone behind the stope face. On the other hand, the selected spatial model dimensions ensure that the influence of the so-called “edge effects” arising from the application of boundary conditions on the model faces is absent. This factor improves the adequacy and reliability of the results obtained for the calculation of the geomechanical model SSS.

Secondly, the determined parameters of the frontal bearing pressure zone are quite consistent with the data range obtained by most researchers. Thus, the frontal bearing pressure developed into the seam roof is observed up to 23 – 25 m. More significant concentrations of the level 1.46 – 1.56 extend up to a height of 11.0 m, and individual local areas appear at a distance of up to 16.2 m. The width of this zone (with an average concentration in the area of 1.5) is 5.2 – 6.0 m, and the beginning of the stope face influence is manifested at a distance of 20 – 25 m, which is quite consistent with the results of mine observations in the Western Donbass.

Thus, for all generally recognized zones of rock pressure anomalies, there is a quite satisfactory correspondence with existing ideas, experimental and analytical studies of the coal-bearing stratum behavior in the area of stope operations.

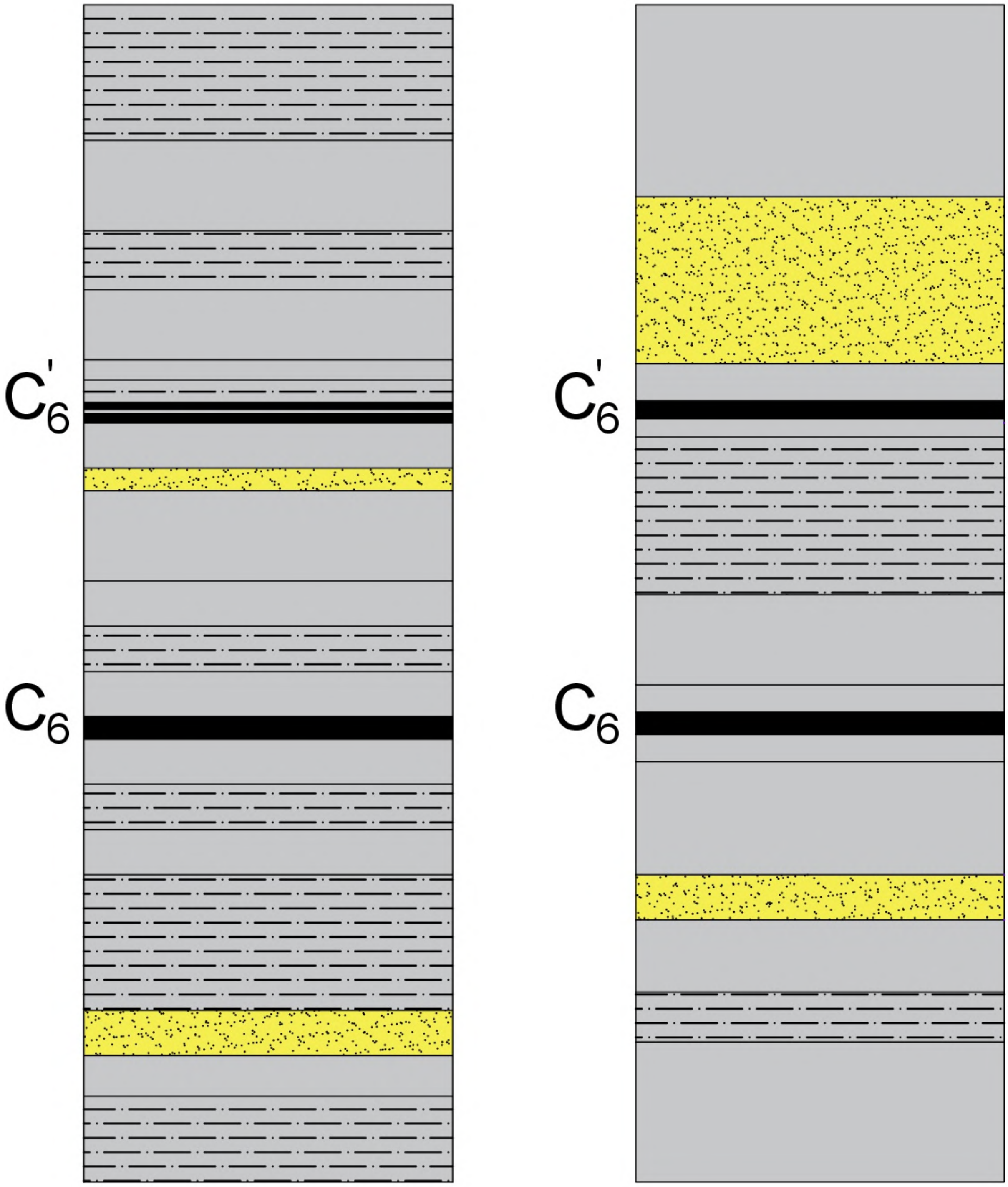
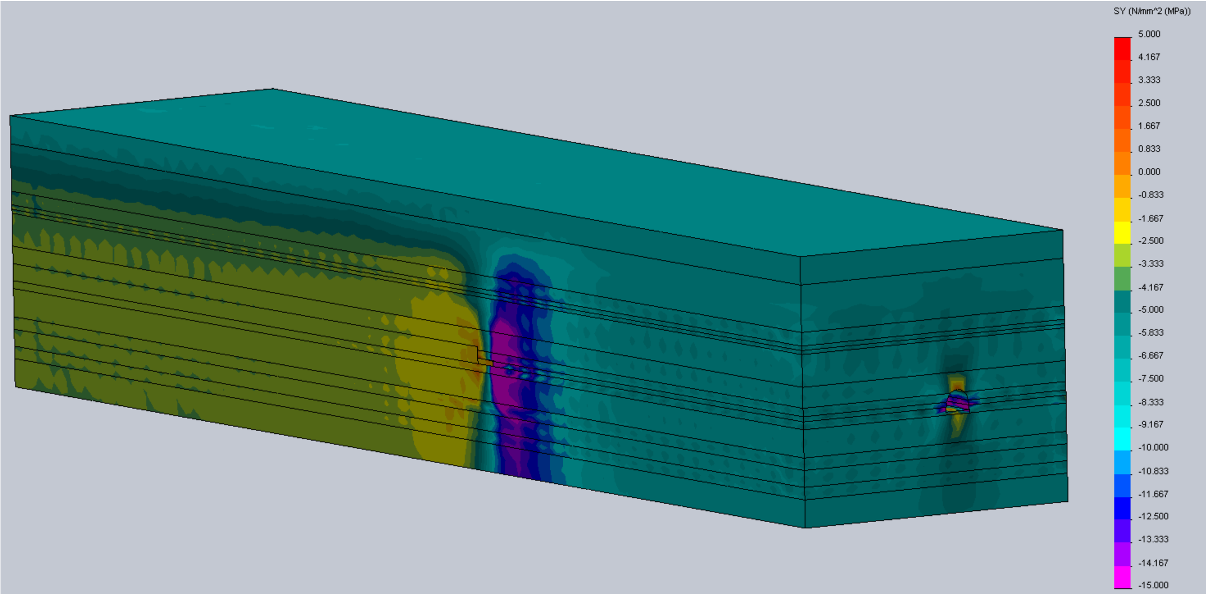


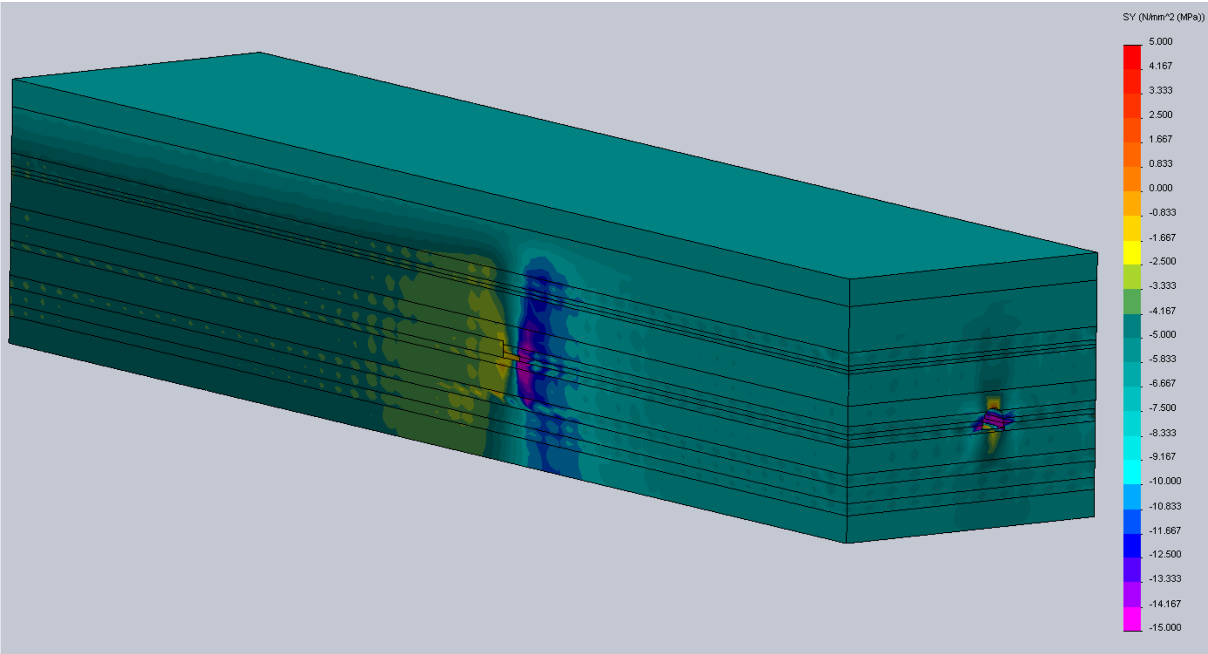
Figure 5. Textural types of the coal-bearing stratum: predominantly thin-bedded and medium-bedded; predominantly thick-bedded and medium-bedded.

5. Change in the SSS of spatial models at different stope face advance velocities

After substantiating the adequacy of the spatial models, six computational experiments is performed, the main task of which is to assess the degree of influence of the stope face advance velocity and the coal-bearing stratum texture on the parameters of rock pressure anomalies in



(a)



(b)

Figure 6. Curves of vertical stresses σ_y in a spatial model of a predominantly thick-bedded and medium-bedded mass at an increased (a) and decreased (b) stope face advance velocity.

the area of the stope face.

A comparative analysis of the SSS components of spatial models is conducted, where, for example, the minimum value of the average daily velocity $V_d = 5$ m/day of the stope face advance is taken as the base. For it, the main parameters of rock pressure anomalies are determined in the form of concentrations of stress components (or the degree of their destressing) and the propagation distances of these concentrations into the mass. At two other values of V_d (10 m/day and 15 m/day), the same order of research is set and the result is presented in relative units of change (increase, decrease) of certain parameters of rock pressure anomalies.

The obtained results in terms of the V_d influence on the dimensions of the frontal bearing pressure zone are presented in the form of graphs (figure 7) for a more visual representation of the correlation degree between the studied parameters. The non-linearity of the growth in the relative dimensions of the frontal bearing pressure zone with an increase in the average daily velocity V_d of the stope face advance is clearly observed. At the V_c of 10 m/day, there is a decrease in the increase gradient P. It should be clarified that when constructing these graphs and subsequent ones, average values of P are taken in each range of vertical stress σ_y concentration coefficients K_y. The general conclusion on the frontal bearing pressure zone dimensions is such that the velocity V_d has a very significant influence (in the range of $V_d = 5$ – 15 m/day), varying in the range from 132 percent to 281 percent.

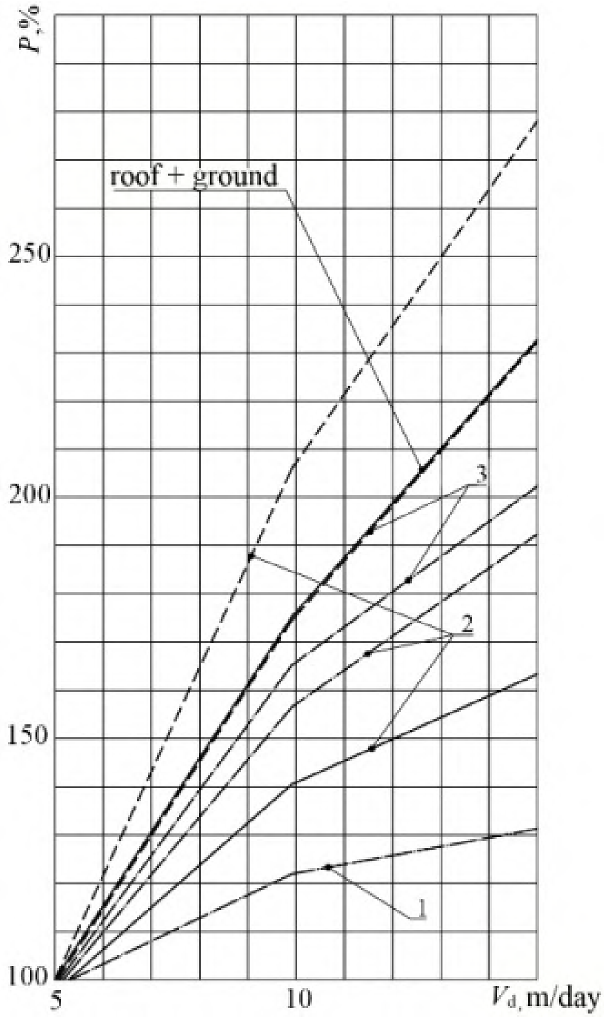


Figure 7. Patterns of the average daily velocity V_d influence of the stope face advance on the growth of the relative dimensions P of the frontal bearing pressure zone at concentration coefficients σ_y.

Similar patterns of the average daily velocity V_d influence of the stope face advance are shown in figure 8 for the dimensions P (at different concentration coefficients K_y) of the lateral bearing pressure zone. The main difference is in the relatively lower degree of influence from 100 percent (no link between P and V_d) to 163 percent for most dimensions of this zone. The only exception is the propagation distance of the concentration $K_y = 1.25 - 1.35$ into the seam bottom. It is noteworthy that the concentration $K_y = 2.0$, which is capable of weakening the border rocks, practically does not change its propagation with an increase in V_d by 3 times (from 5 to 15 m/day). This means a sufficient constancy of the dimensions of weakened rocks from the side of the undisturbed rock mass and, at least, the absence of an increase in the mass displacements (in this direction), if the time factor of their development is not taken into account (limitation of displacements at high values of V_d). Lower concentrations σ_y propagate to more remote areas at $V_d = 10 - 15$ m/day, but it is their moving away (up to 13–15 m along the strike) that makes it possible to predict the minimum impact from the undisturbed rock mass on the rock pressure manifestations in the extraction drift.

In the destressing zone behind the stope face, similar tendencies in the velocity V_d influence on this rock pressure anomaly values are observed (figure 9).

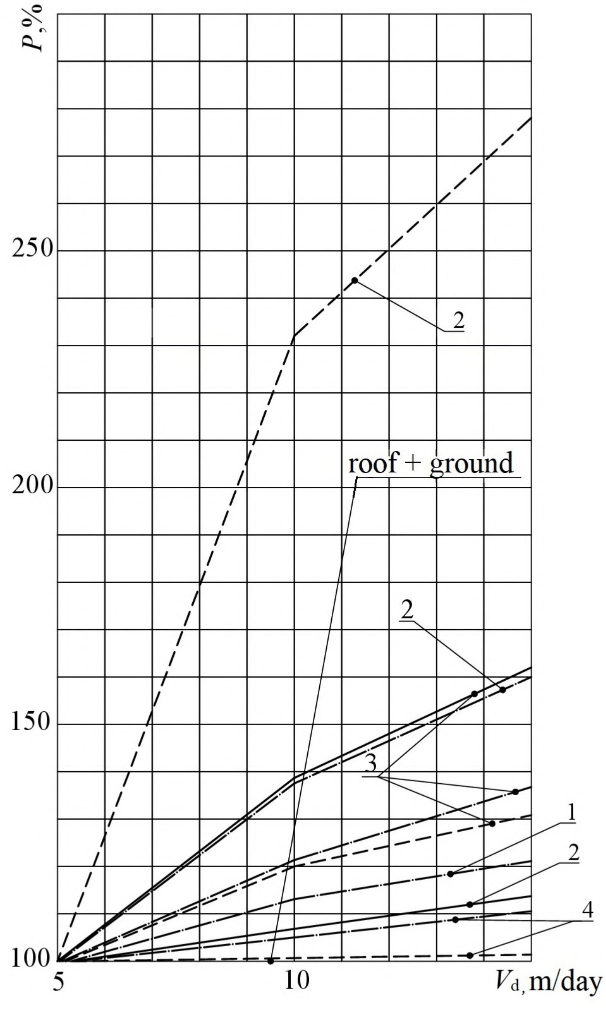


Figure 8. Patterns of the average daily velocity V_d influence of the stope face advance on the growth of the relative dimensions P of the destressing zone at concentration coefficients σ_y.

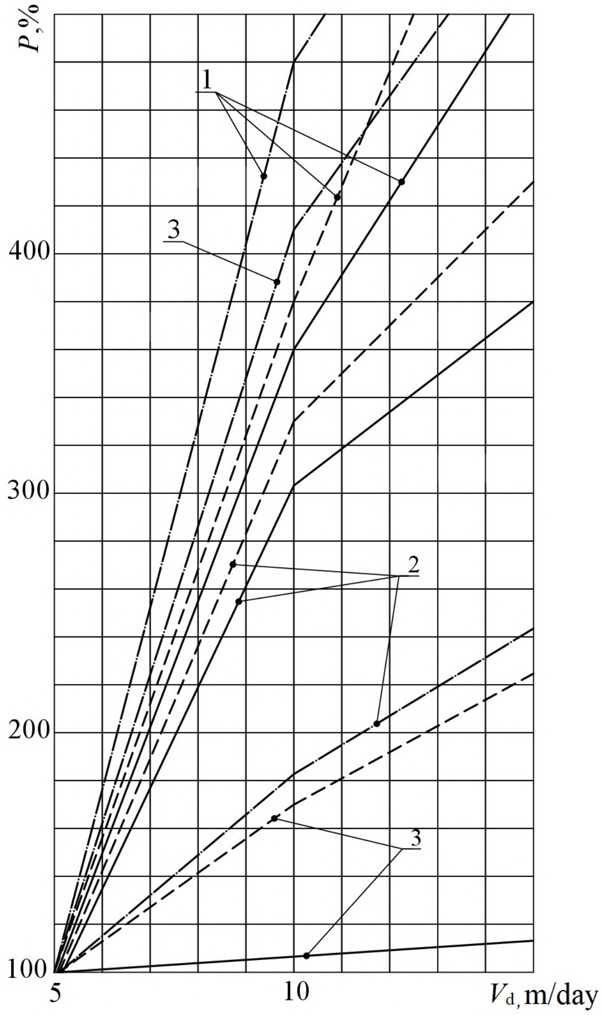
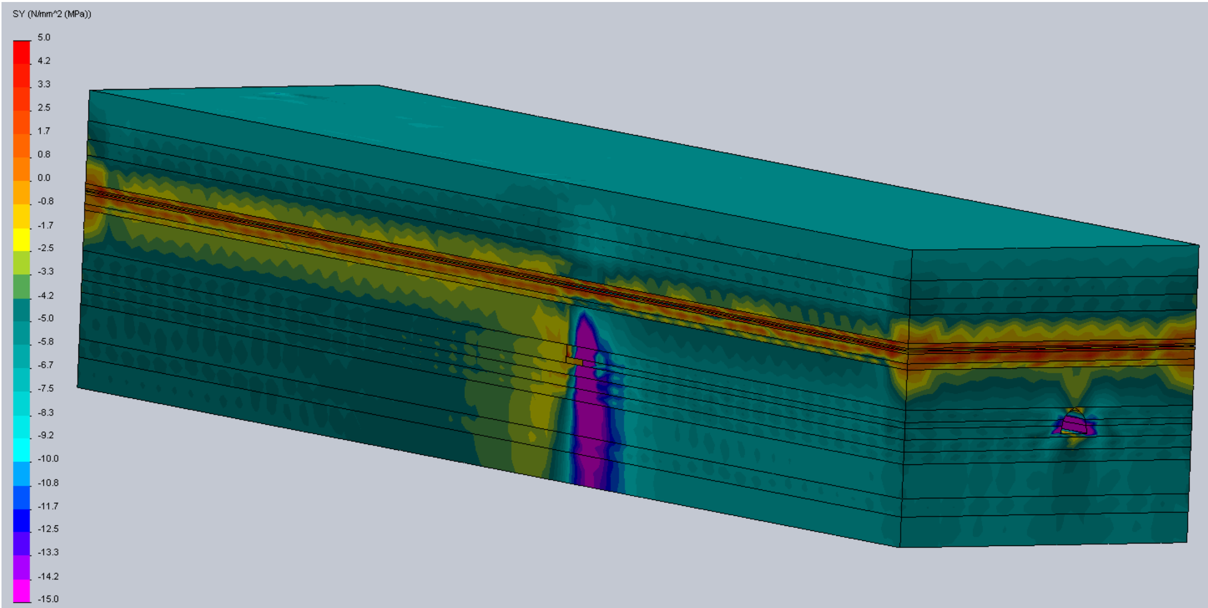


Figure 9. Patterns of the average daily velocity V_d influence of the stope face advance on the growth of the relative dimensions P of the lateral bearing pressure zone at concentration coefficients σ_y.

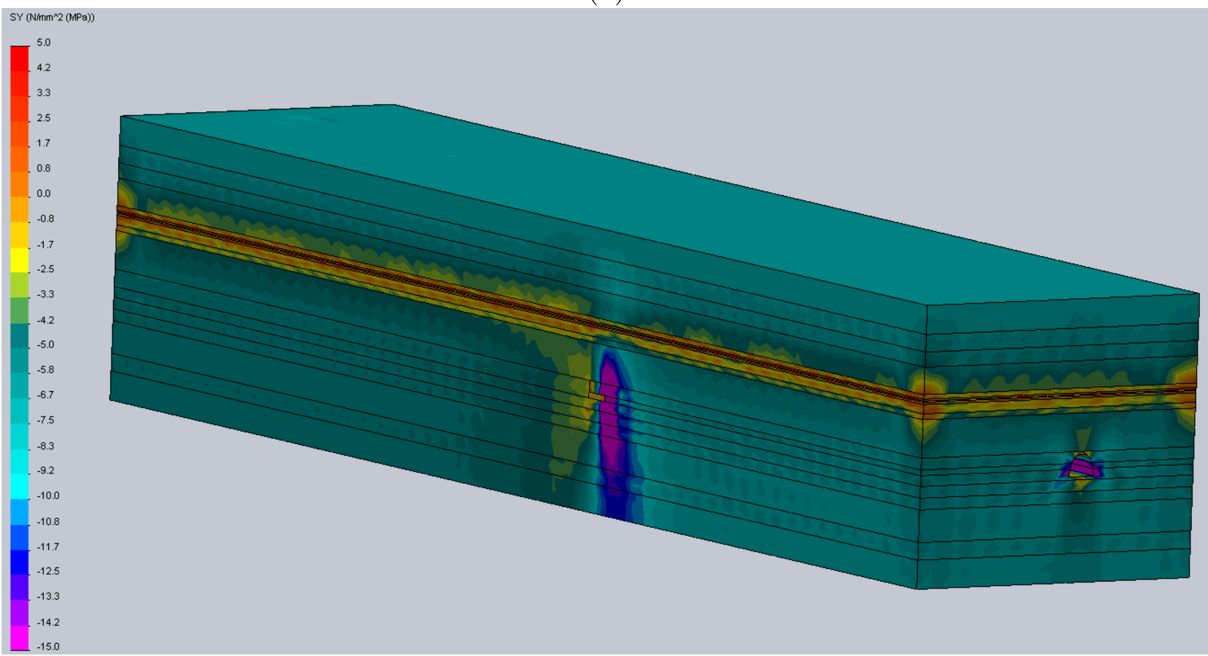
6. Influence of the coal-bearing mass texture on the stress-strain state of spatial models

The studies accumulated to date on the stratified coal-bearing mass stress-strain state, including the Western Donbass weak rocks, convincingly prove the presence of the influence of its texture on the parameters of distributing stress components in the area of stope operations. Therefore, this factor is subjected to a detailed study in combination with a variable velocity of the stope face advance. The studies are illustrated by the example of spatial curves of the three stress components distribution: vertical σ_y, horizontal σ_z (in the plane of the cross-section of extraction workings) and stress intensity σ.

First of all, the peculiarities of vertical stress distribution are studied, the curve of which is shown in figure 10 for the minimum ($V_d = 5$ m/day) and maximum ($V_d = 15$ m/day) stope face advance velocities in the studied range of their change. Since the analysis of the distribution parameters σ_y for a predominantly thick-bedded and medium-bedded structure has already been presented, the results of comparison with the peculiarities of the curve σ_y for a predominantly thin-bedded and medium-bedded structure are presented below.



(a)



(b)

Figure 10. Curves of vertical stresses σ_y in a spatial model of a predominantly thin-bedded and medium-bedded mass at an increased (a) and decreased (b) stope face advance velocity.

At the minimum stope face advance velocity ($V_d = 5$ m/day), the following differences in the distribution curve σ_y for predominantly thin-bedded and medium- bedded texture of the coal-bearing stratum have been revealed.

In the frontal bearing pressure zone, the change in the mass texture has caused a number of transformations in the vertical stress σ_y distribution. Thus, the minimum influence of the approaching stope face ($K_y = 1.05 - 1.25$) is noted at a distance of $13 - 15$ m to the rise of the seam. This is by 35 – 40 percent closer to the stope face than with predominantly thick-bedded and medium-bedded texture. This is quite consistent with the results of mine observations of rock pressure manifestations and is explained as follows: less thick rock layers that are not capable of developing a high repulse reaction to vertical rock pressure weaken and break into blocks with a small length of a stable cantilever, which deform the underlying layers at a greater distance (to the rise) from the stope face.

The minimum concentration of $K_y = 1.05 - 1.25$ propagates into the seam roof up to 23 – 24 m, which practically coincides with the results of the predominantly thick-bedded and medium-bedded texture variant. Into the seam bottom, the minimum concentrations are distributed to an equivalent depth and go beyond the boundaries of the spatial model.

More significant concentrations of the $K_y = 1.46 - 1.56$ level reach 2.5 – 4.6 m to the rise from the stope face plane, that is, they reduce their impact by 23 – 52 percent. This concentration in the roof reaches 6.7 m (decrease by 39 percent), and in the bottom – 18.6 m, which is by 2.04 times higher than in the predominantly thick-bedded and medium-bedded texture.

The most dangerous concentrations of $K_y = 2.0$ level are located near the stope face and are characterized by the following dimensions: to the rise of the seam – 2.1 – 2.6 m (81 – 87 percent); throughout the height into the roof – up to 4.6 m (by 1.19 times greater); in depth of the bottom – up to 11 m (by 2.29 times greater).

Summing up the above data, one should pay attention to the tendencies of reducing the propagation of concentrations σ_y to the rise of the seam and mainly the growth of their dimensions into the roof and bottom of the seam.

The obtained tendencies in terms of the development of rock pressure manifestations in the extraction workings make it possible to predict the following:

- reduction not only of the distance (ahead of the stope face) of the coal-bearing mass displacement intensity into the cavity of mine workings, but also the value of their displacements;
- directly near the junction of the stope face with the drift, an increase in the displacement velocity of the rocks in the roof and the bottom of the seam.

In general, according to the results of the performed studies on the stress-strain state of spatial models, a number of influence patterns of the coal-bearing mass texture type and the average daily velocity of the stope face advance on the parameters of the three main rock pressure anomalies in the area of conducting stope operations have been determined: frontal and lateral bearing pressure zones, as well as destressing zone behind the stope face.

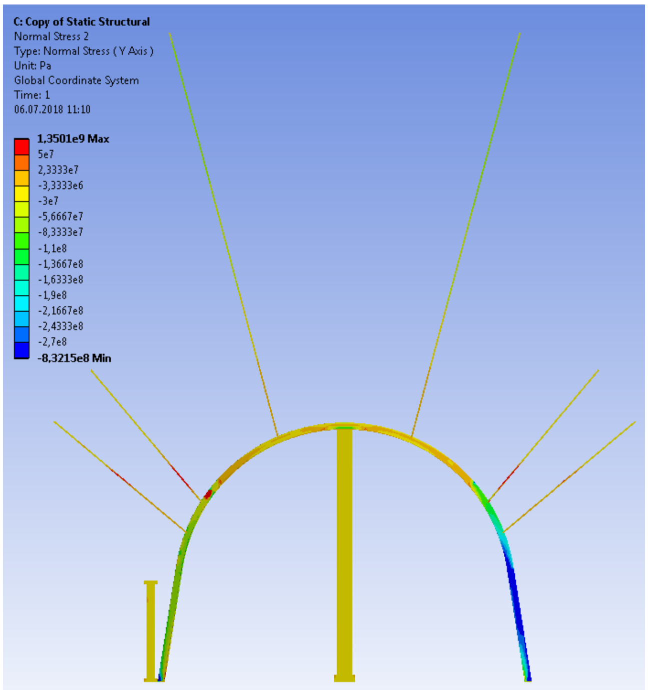
These studies are used in the development of recommendations for the selection of rational design parameters for high-rate mining of coal seams in the Western Donbass conditions.

Based on the performed research, the state of modern fastening and security structures has been studied, which provides the possibility of reusing the mine working at high velocities of stope face advance in order to improve the schemes for maintaining extraction workings.

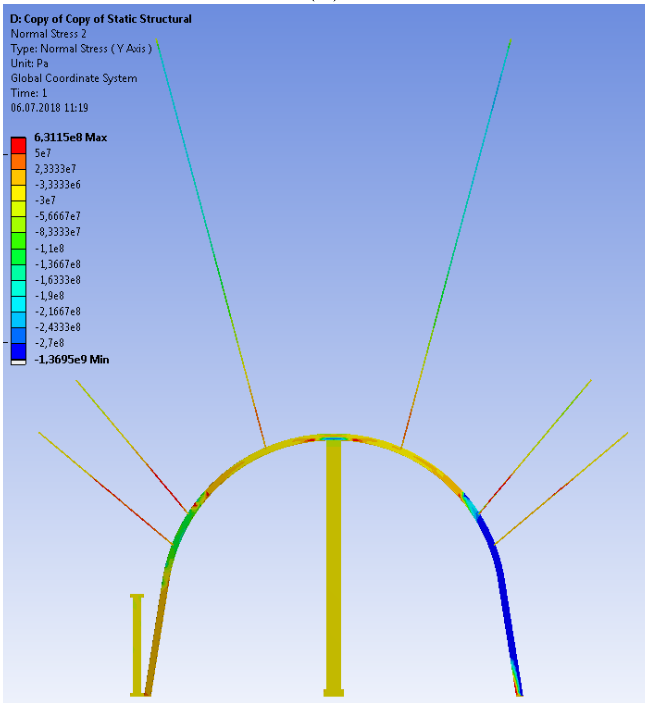
The state of the fastening and security structures is studied in terms of three main stress components. The SSS analysis is performed sequentially for each of the studied areas of the mine working maintenance.

For example, a curve of the vertical stress σ_y components is studied (figure 11).

The conducted comparative analysis of the vertical stress distribution in all fastening structure elements proves the significance of the influence of the stope face advance velocity and the mass texture. The identified tendencies should be taken into account when substantiating the fastening parameters. The patterns determined during the performance of multivariate computational observations have been confirmed in the course of instrumental observations in the mine workings of the Western Donbass mines (figure 12).



(a)



(b)

Figure 11. Curves of vertical stresses σ_y iin the fastening structure of the extraction drift in the frontal bearing pressure zone at the stope face advance velocities V_d: (a) $V_d = 15$ m/day; (b) $V_d = 5$ m/day.

Figure 12. The state of mine working at the experimental site.

Experimental studies have been performed in various mining-geological and mining-technical conditions.

The decrease in the material consumption of fastening and security structures at high velocities of advancing stope faces has been substantiated and confirmed by calculations. It is recommended to fasten with the lightweight SCP-22 profile and with an increase in the step of setting the frame support and resin-grouted rockbolts up to 1.0 m, the rope bolts are placed in a checkerboard pattern with a step of 4.0 m, the permissible diameter and the number of rows of side prop stays of the strengthening support and the breaker-prop row are reduced. The use of such a highly efficient scheme for maintaining extraction workings provides a reduction in the time and cost spent on end operations. Thus, this creates an opportunity for the full operation of modern high-performance stope equipment and, as a result, the intensification of mining operations in difficult mining-geological conditions.

7. Conclusions

Generalization of the research results makes it possible to formulate the following conclusions.

The analysis of existing analytical studies and experimental measurements of the rock pressure manifestation parameters has convincingly proved the significance of the influence of technological parameters of coal seam mining on the formation of SSS anomalies (frontal and lateral bearing pressure, destressing zone behind the stope face) in the coal-bearing mass adjacent to stope operations. For indicated three main SSS anomalies, a set of parameters has been substantiated that completely characterize this research object. On the other hand, two technological parameters have been distinguished that not only significantly influence on the formation and development of SSS anomalies, but are also inextricably linked with the intensification of mining the coal seams: the average daily velocity V_d of the stope face advance and the duration of its stoppage t.

Based on the analysis of existing scientific-practical developments, the most expedient three-stage structure for performing research has been substantiated, where mine instrumental observations and multivariate computational experiments are combined and complement each other through a linking element – the mechanism for coal-bearing mass displacement in terms of the impact of the selected technological parameters for conducting stope operations.

A new methodological approach has been developed in the technology of conducting computational experiments, which ensures the research continuity when separating and sequentially solving two groups of problems on a common macromodel and subordinate models with a more detailed reflection of real conditions. Such a two-stage research structure makes it possible to more adequately and reliably determine two groups of patterns of the influence of technological parameters on the indicators of rock pressure anomalies and stress-strain state of fastening, security elements in the latest schemes for resource-saving maintenance of extraction workings in the conditions of highly stressed stope faces.

Six main peculiarities of the substantiation and construction of geomechanical models have been formulated and systematized, with account of which it is possible to ensure a sufficient degree of adequacy and reliability of the results of computational experiments for studying the correlation between the rock pressure anomaly parameters and mining-geological, technological factors of highly-productive mining of coal seams.

It has been proved that the results of calculating the SSS of spatial geomechanical models correspond to the prevailing ideas about the mechanism and nature of the coal-bearing stratum displacement process in the zone of stope operations. The consistency of the results and their objectivity has been determined based on the analysis of the parameters of rock pressure anomalies.

A very significant influence of the average daily velocity V_d of the stope face advance (in the range of changing $V_d = 5 - 15$ m/day) on the dimensions P of the frontal bearing pressure zone has been determined. The link between P and V_d is non-linear with some damping of the growth gradient of the zone dimensions at $V_c = 10$ m/day. The average values of increasing P at $V_d =$ 15 m/day are from 132 percent (to the rise of the seam at $K_y = 1.05 - 1.25$) to 281 percent (in depth of the bottom at $K_y = 1.46 - 1.56$). The revealed patterns should be taken into account when choosing the mode for conducting stope operations and, especially, when substantiating the parameters of the fastening structures and the means of their strengthening (ahead of the stope face) for the extraction drifts.

A reduced influence of V_d on the dimensions P of the lateral bearing pressure zone has been revealed. Moreover, the distribution of "destructive" vertical stress σ_y concentrations practically does not change in the range of 5 m/day V_c 15 m/day. On the other hand, reduced concentrations σ_y that are influenced by V_d cannot significantly affect the rock pressure manifestations in the extraction drift due to their remoteness. This brings to the fore the pattern for limiting the adjacent mass displacement at high velocities of the stope face advance.

A tendency to reduce the influence of the stope face advance velocity on the dimensions of the frontal bearing pressure zone with a more thin-bedded mass texture compared to a thick-bedded texture has been revealed. This is conditioned by the reduced stability of less thick lithotypes, which, during their bending, "react" to a lesser extent to limiting the period of acting bending loads at increased stope face movement velocities. At the same time, in the zone of lateral bearing pressure (in the area of the drift ahead of the stope face, where the maximum frontal bearing pressure acts), the opposite tendency has been determined – an almost universal increase in the degree of V_d influence on the dimensions of the zone under conditions of a more thin-bedded mass texture. In the destressing zone, there is a decrease in the degree of V_d influence, similar to the tendencies in the frontal bearing pressure zone.

The results of research in various mining-geological conditions are experimentally confirmed, as well as recommendations for the implementation of resource-saving fastening and security systems are presented.

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References

[1] Dyczko A, Kamiński P, Jarosz J, Rak Z, Jasiulek D and Sinka T 2022 *Energies* **15**(1) 95 URL https://doi.org/10.3390/en15010095
[2] Bazaluk O, Rysbekov K, Nurpeisova M, Lozynskyi V, Kyrgizbayeva G and Turumbetov T 2022 *Frontiers in Environmental Science* **10** URL https://doi.org/10.3389/fenvs.2022.852591
[3] Bondarenko V, Kovalevska I, Cawood F, Husiev O, Snihur V and Jimu D 2021 *Mining of Mineral Deposits* **15**(1) 1–10 URL https://doi.org/10.33271/mining15.01.001
[4] Małkowski P, Niedbalski Z, Majcherczyk T and Bednarek L 2020 *Mining of Mineral Deposits* **14**(3) 1–14 URL https://doi.org/10.33271/mining14.03.001
[5] Skipochka S 2019 *E3S Web of Conferences* **109** 00089 URL https://doi.org/10.1051/e3sconf/201910900089
[6] Lozynskyi V, Saik P, Petlovanyi M, Sai K and Malanchuk Y 2018 *International Journal of Engineering Research in Africa* **35** 77–88 URL https://www.scientific.net/JERA.35.77
[7] Fomichov V, Pochepov V, Sotskov V and Mamaikin O 2018 *ARPN Journal of Engineering and Applied Sciences* **13**(7) 2381–2389 URL http://www.arpnjournals.org/jeas/research_papers/rp_2018/jeas_0418_6941.pdf
[8] Fomychov V, Mamaikin O, Demchenko Y, Prykhorchuk O and Jarosz J 2018 *Mining of Mineral Deposits* **12**(4) 46–55 URL https://doi.org/10.15407/mining12.04.046
[9] Shashenko O M, Hapieiev S M, Shapoval V G and Khalymendyk O V 2019 *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu* **1**(1) 28–36 URL http://nvngu.in.ua/index.php/en/archive/on-the-issues/1707-2019/contens-1-2019/mining/4768-analysis-of-calculation-models-while-solving-geomechanical-problems-in-elastic-approach
[10] Matayev A, Kainazarova A, Arystan I, Abeuov Y, Kainazarov A, Baizbayev M, Demin V and Sultanov M 2021 *Mining of Mineral Deposits* **15**(1) 103–111 URL https://doi.org/10.33271/mining15.01.103
[11] Bondarenko V I, Kovalevska I A, Podkopaiev S V, Sheka I V and Tsivka Y S 2022 *IOP Conference Series: Earth and Environmental Science* **1049** 012026 URL https://doi.org/10.1088/1755-1315/1049/1/012026
[12] Babets D, Sdvyzhkova O, Shashenko O, Kravchenko K and Cabana E C 2019 *Mining of Mineral Deposits* **13**(4) 72–83 URL https://doi.org/10.33271/mining13.04.072
[13] Bondarenko V, Kovalevska I, Symanovych G, Sotskov V and Barabash M 2018 *Mining Science* **25** 219–235 URL https://doi.org/10.5277/msc182515
[14] Małkowski P, Ostrowski L and Stasica J 2022 *Energies* **15**(12) 4340 URL https://doi.org/10.3390/en15124340
[15] Kovalevs'ka I, Illiashov M, Fomychov V and Chervatuk V 2012 The formation of the finite-element model of the system "undermined massif-support of stope" *Geomechanical Processes During Underground Mining - Proceedings of the School of Underground Mining* pp 73–79
[16] Sotskov V O, Demchenko Y I, Salli S V and Dereviahina N I 2017 *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu* (6) 34–40 URL https://tinyurl.com/2364d4uf
[17] Malashkevych D, Sotskov V, Medyanyk V and Prykhodchenko D 2018 *Integrated evaluation of the worked-out area partial backfill effect of stress-strain state of coal-bearing rock mass* (*Solid State Phenomena* vol 277) URL https://www.scientific.net/SSP.277.213

[18] Krukovskyi O, Bulich Y, Kurnosov S, Yanzhula O and Demin V 2022 *IOP Conference Series: Earth and Environmental Science* **970** 012049 URL https://doi.org/10.1088/1755-1315/970/1/012049
[19] Krykovskyi O, Krykovska V and Skipochka S 2021 *Mining of Mineral Deposits* **15**(4) 8–14 URL https://doi.org/10.33271/mining15.04.008
[20] Bulat A F and Chekhov V N 1994 *International Applied Mechanics* **30**(8) 593–598 URL https://doi.org/10.1007/BF00847231
[21] Bulat A F and Chekhov V N 1992 *Prikladnaya Mekhanika* **28**(12) 64–71
[22] Fomychov V, Fomychova L, Khorolskyi A, Mamaikin O and Pochepov V 2020 *ARPN Journal of Engineering and Applied Sciences* **15**(24) 3039–3049 URL http://www.arpnjournals.org/jeas/research_papers/rp_2020/jeas_1220_8449.pdf
[23] Khorolskyi A, Hrinov V, Mamaikin O and Fomychova L 2020 *E3S Web of Conferences* **201** 01030 URL https://doi.org/10.1051/e3sconf/202020101030
[24] Khorolskyi A, Hrinov V, Mamaikin O and Demchenko Y 2019 *Mining of Mineral Deposits* **13**(4) 53–62 URL https://doi.org/10.33271/mining13.04.053
[25] Bondarenko V, Kovalevska I, Sheka I and Sachko R 2023 *IOP Conference Series: Earth and Environmental Science* **1156** 012011 URL https://doi.org/10.1088/1755-1315/1156/1/012011/meta
[26] Mamaikin O, Sotskov V, Demchenko Y and Prykhorchuk O 2018 *E3S Web of Conferences* **60**
[27] Lozynskyi V, Medianyk V, Saik P, Rysbekov K and Demydov M 2020 *Rudarsko Geolosko Naftni Zbornik* **35**(2) 23–31 URL https://www.researchgate.net/publication/340909739
[28] Hrinov V and Khorolskyi A 2018 *E3S Web of Conferences* **60** 00017 URL https://doi.org/10.1051/e3sconf/20186000017
[29] Khorolskyi A, Mamaikin O, Fomychova L, Pochepov V and Lapko V 2022 *Collection of research papers of the National mining university* **64**(08) 99–111 URL https://doi.org/10.33271/crpnmu/64.099
[30] Nurpeisova M B, Bitimbayev M Z, Rysbekov K B and Bekbasarov S S 2021 *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu* **6**(6) 5–10 URL https://doi.org/10.33271/nvngu/2021-6/005
[31] Fomichov V V, Sotskov V A and Malykhin A V 2014 *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu* **1**(1) 22–26 URL https://tinyurl.com/5n8dj67j
[32] Małkowski P, Niedbalski Z and Balarabe T 2021 *International Journal of Coal Science and Technology* **8**(2) 312–323 URL https://doi.org/10.1007/s40789-020-00369-2
[33] Snihur V 2022 *Collection of research papers of the national mining university* **68**(06) 67–80 URL https://doi.org/10.33271/crpnmu/68.067
[34] Sdvyzhkova O and Patyńska R 2016 *Studia Geotechnica et Mechanica* **38**(1) 91–98 URL https://www.researchgate.net/publication/307837529
[35] Sotskov V and Gusev O 2014 Features of using numerical experiment to analyze the stability of development workings *Progressive Technologies of Coal, Coalbed Methane, and Ores Mining* vol 1 ed Bondarenko V, Kovalevs'ka I and Ganushevych K (CRC Press) pp 401–404
[36] Skipochka S, Krukovskyi O, Palamarchuk T and Prokhorets L 2020 *Mining of Mineral Deposits* **14**(4) 24–30 URL https://doi.org/10.33271/mining14.04.024
[37] Sakhno I, Sakhno S and Isaienkov O 2022 *Mining of Mineral Deposits* **16**(4) 1–10
[38] Bulychev N S 1980 *Mechanics of underground structures* (Moscow: Nedra)
[39] Shavarskyi I, Falshtynskyi V, Dychkovskyi R, Akimov O, Sala D and Buketov V 2022 *Mining of Mineral Deposits* **16**(3) 78–85 URL https://doi.org/10.33271/mining14.02.085
[40] Kolumbetova K K 2021 *Engineering Journal of Satbayev University* **143**(4) 31–40 URL https://doi.org/10.51301/vest.su.2021.i4.05
[41] Mukha O, Cheberiachko Y, Sotskov V and Kamulin A 2019 *E3S Web of Conferences* **123** 01048 URL https://doi.org/10.1051/e3sconf/201912301048
[42] Fomichev V V 2012 *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu* **4** 54–59 URL https://tinyurl.com/463cpupc
[43] Nithiarasu P and Zienkiewicz O C 2000 *International Journal for Numerical Methods in Engineering* **47**(1-3) 629–662 URL https://doi.org/10.1002/(SICI)1097-0207(20000110/30)47:1/3%3C629::AID-NME786%3E3.0.CO;2-Y
[44] Zienkiewicz O C 2000 *International Journal for Numerical Methods in Engineering* **47**(1-3) 9–28 URL https://doi.org/10.1002/(SICI)1097-0207(20000110/30)47:1/3%3C9::AID-NME793%3E3.0.CO;2-P

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Useful nanoparticles from mining waste and acid mine drainage

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Useful nanoparticles from mining waste and acid mine drainage

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Abstract. Mining waste can generate environment pollution including acid mine drainage (AMD). AMD is dangerous for its surroundings and can pollute surface and groundwater it is contacting with. Nanomaterials are advanced materials used in all fields of human activity and development. However, their production is still expensive and may pollute the environment due to the chemicals' used and/or production of the energy needed for their synthesis. A smart solution could be use of mining waste and AMD to produce nanomaterials with properties similar to the properties of nanomaterials obtained from clean chemicals. Thus both waste will be valorised / decontaminated and useful and needed materials produced. This paper presents production of nanoparticles and nanomaterials from mining waste and AMD with emphasis on iron- and copper-based materials, as well as some applications of the obtained materials.

1. Introduction

Mining and minerals beneficiation are fundamental activities that provide raw materials for the production of goods and services necessary for the daily life of every person, as well as for the sustainable development of all humanity.

However, large amounts of solid rocky waste and tailings are generated that, apart from their unaesthetic appearance, can be a source of dangerous environmental pollutants resulting from the leaching of usually present toxic metals, metalloids and/or non-metals under the influence of precipitation [1, 2]. This type of waste has been accumulated for hundreds and thousands years and some authors estimate that its yearly production rate is 350x109 t [3] while other give the value of 100x109 t waste from primary production of mineral and metal commodities [4]. Although the mining waste disposal decreases in some well-developed countries, due to their ability to treat, recycle or use for energy recovery part of this waste this is not the case with all countries worldwide.

Scientific and engineering community has already been working on the technologies for mining waste management [4,5] and for extraction of valuable metals from mining and mineral processing waste [6–10].

Mining activities and mine waste can be a source of mine drainages that can be four types (neutral, acid, basic and saline) in dependence of the ores composition and local hydro-geological and physicochemical conditions. Among the mentioned types, acid mine drainage (AMD) represents the major concern. Generally, its formation can be presented by the following chemical equations [11, 12]:

$$2FeS_{2(s)} + 7O_{2(g)} + 2H_2O \rightarrow 2Fe^{2+}_{(aq)} + 4SO^{2-}_{4(aq)} + 4H^{+}_{(aq)},$$
$$4Fe^{2+}_{(aq)} + O_{2(g)} + 4H^{+}_{(aq)} \rightarrow 4Fe^{3+}_{(aq)} + 2H_2O,$$
$$FeS_{2(s)} + 14Fe^{3+}_{(aq)} + 8H_2O \rightarrow 15Fe^{2+} + 2SO^{2-}_{4(aq)} + 16H^{+},$$
$$Fe^{3+}_{(aq)} + 3H_2O \rightarrow Fe(OH)_{3(s)} + 3H^{+}.$$

The pyrite (FeS_2) oxidation can be facilitated by the presence of sulphur-oxidizing bacteria. The acidic nature of the AMD leads to the leaching of the ores that it is contacting with and thus different metals, such as aluminium (Al), cadmium (Cd), chromium (Cr), cobalt (Co), copper (Cu), manganese (Mn), nickel (Ni), lead (Pb), zinc (Zn), etc. and metalloids (for example, arsenic – As) appeared in the AMD, besides iron (Fe). AMD is dangerous for the surrounding environment or when it mixes with surface or groundwater bodies. The composition and characteristics of AMD depends on the local geological, hydro-geological and climate conditions, availability of pyrite ores and the rate of their oxidation. Without any claims for comprehensiveness, table 1 gives an idea about the ranges of some AMD parameters.

Table 1. Concentration ranges of some metals and As in AMD from different mines worldwide.

Parameter, Pollutants concentration range, mg L^{-1}	Coal mines [11–15]	Sulfide ores mines* [12, 13, 16, 17]	Copper mines [12, 18, 19]	Pyrite mines [12, 13, 17]
pH	2.43-3.23	1.9-2.7	2.2-5.2	2.1-2.7
Al	17.7-668.8	9.1-260	0.44-382.6	117-1878
As	0.06-3.52	n.i.	n.i.	n.i.
Cd	0.01-0.05	0.10-163.8	0.04-0.9	0.01
Co	0.14-1.87	45-163	0.12	n.i.
Cu	0.06-0.45	0.23-77.3	14.7-531.2	0.02-165
Fe	105.3-6051	16.7-2040	1.1-413	153-3580
Mn	12.2-128.0	13.7-210.7	66.3-72.0	21.9-467
Ni	0.03-3.48	0.13-312	0.22	n.i.
Pb	0.03-0.18	0.1-45.0	n.i.	0.13-0.40
Zn	0.2-25.0	4.4-410	1.11-133	4.9-976

* Cu-Zn, Pb-Zn, Cu-Pb-Zn, and polymetallic ores; n.i. – no information

It is difficult to prevent formation of AMD because it is a natural oxidation process accelerated by the increase in pyrite-bearing minerals surface area that is exposed to water and oxygen during mining operations [14]. The already formed AMD is treated in active and/or passive systems. Constructed wetlands, limestone drains, permeable reactive barriers, and use of natural sulphate reduction processes are the main passive treatment methods. They could be more cost effective and environmentally friendly, compared to active methods, but are slow and depend on the site conditions [12]. Most often the active treatment is based on addition of neutralizing and alkalizing reagents, mainly lime, limestone, magnesite, etc. [11, 20]. However, alkalization precipitation of metals-pollutants results in big amount of sludge. In addition, the metals in the sludge could be relatively easily mobilized by contacting with acidic or even fresh water. Thus, this type of treatment needs corresponding handling and storage. Adsorption is considered as a cost-effective and efficient method in treating AMD. Different adsorbents are used, among them natural mineral materials such as clays and zeolites. Their low mechanical strength and poor ion selectivity can be pointed as drawbacks. Membrane technologies such as nanofiltration and reverse osmosis possess high separation efficiency, automatic operation and produce good water quality. However they are still relatively expensive and need a preliminary treatment of the water in order to reduce membrane system pollution and unstable work [12].

Recovery of the valuable metals from AMD and solid mining waste is needed in order to achieve sustainable use of resources jointly with sustainable remediation and the environment protection.

Nanomaterials are materials that have at least one dimension at nanoscale. Due to their size, nanomaterials have a number of different properties compared to bulk materials of the same chemical composition [14]. They are used in different areas such as electronics, power generation and storage, mechanical industries, water treatment, pharmaceutical and medical activities and products, etc. [21, 22]. Recently magnetic zeolite nanocomposites have been studied as reusable green adsorbents for removal of different pollutants from wastewater [23, 24].

Two approaches are applied to synthesize nanoparticles (NPs). The "top-down" approach is based on a physical miniaturization of materials to the nanometer scale by applying high-energy inputs. Mechanical milling, laser ablation, ion sputtering, etc. are included in this approach. The "bottom-up" approach is based mainly on chemical reaction of precursors and precipitation of the obtained NPs or evaporation followed by deposition. Both techniques for NPs production are expensive and can pollute the environment by using chemicals and/or due to the production of the energy needed. The basis of the NPs biosynthesis is the use of biochemical redox reactions where the ion is transformed to its solid phase by using as chemicals extracts of different microbes and plants. This approach is considered environmentally-friendly, cost effective and scalable [21, 25] but usually the NPs yield is low.

This paper aim is to present recovery of the valuable metals from mining waste and AMD under the form of useful nanoparticles and nanocomposites and some applications of the produced materials, which is a relatively new scientific field being developed in recent years.

2. Nanoparticles from mining waste

Mining waste contains diverse valuable metals and various technologies have been and are being developed and applied to extract metals. Recent 10-15 years with the burst of nanoscience and nanotechnologies the number of studies on NPs production from mining waste is also increasing. Mainly iron (Fe) mining waste has attracted the scientists' attention probably due to the two reasons: a) diverse unique properties of iron-based nanoparticles and especially of the magnetite nanoparticles (MNPs) and b) due to the mineral beneficiation technology usually this waste is rich in Fe that could be used as a cheap precursor for preparing MNPs.

2.1. Iron-based nanoparticles

Iron based materials and especially magnetite (Fe_3O_4) nanoparticles have found wide application. Back in 2004 Hu and co-workers [26] prepared MNPs ($\sim$ 10 nm) by sol-gel method and studied their ability to remove Cr(VI) from wastewater by adsorption. Adsorption on MNPs is regarded as an effective and economically vital method for removing different pollutants (such as metal ions, dyes) from water [20]. Besides their use as adsorbents MNPs are used as catalysts, paint pigments, additives to ceramics, in electronic materials fabrication, ferrofluid technology, controlled drug delivery, etc. [20, 27].

MNPs are able to remove most divalent and some trivalent metal ions (forming stable precipitates) from water (including AMD) at easy application and recovery by magnetic filtration. In addition, most of them do not change their magnetic properties when used as adsorbents and thus they can be reused [20]. MNPs are synthesized by different methods, such as thermal decomposition, milling, chemical precipitation, sonochemical synthesis. Chemical precipitation is the most widely used approach because the produced MNPs are with controlled size and morphology. Co-precipitation of Fe^{3+} and Fe^{2+} (from aqueous solutions, at a ratio of 2:1) is usually applied to prepare the MNPs.

It is carried out under anaerobic alkaline (pH 9–12) conditions [27]. The cost of iron precursor salts used is the main component contributing to the price of nanoparticles. For this reason, as a source of Fe ions, mining wastes from iron ore mining and processing are of interest for the production of MNPs. In addition, in recent years an increasing attention is paid to the synthesis of iron-based materials, especially aimed to be used in energy storage applications.

2.1.1. Materials based on iron oxides. Wu et al [28] synthesized magnetic Fe_3O_4 nano-powder by applying ultrasonic chemical co-precipitation in presence or absence of a surfactant sodium dodecyl sulfate ($C_{12}H_{25}OSO_3Na$). They used high purity Fe that was separated from iron ore tailings by acidic leaching (with 37.5 wt. % hydrochloric acid – HCl). Further, hydrogen peroxide (H_2O_2) was added to the filtrate (i.e. to the pregnant leach solution – PLS) in order to ensure that all iron exists as Fe^{3+}. The solution was heated to 60°C and concentrated ammonia solution (NH_4OH) was added to achieve pH 3.2. Thus iron was separated from tailings and precipitated as $Fe(OH)_3$. The precipitate formed was washed and re-dissolved in HCl. Measured amount of $FeSO_4 \cdot 7H_2O$ was added in order to ensure Fe^{3+} and Fe^{2+} molar ratio of 1.5:1. Then sodium hydroxide (NaOH) solution was added under ultrasonic agitation to form black precipitate of Fe_3O_4 by the reaction

$$Fe^{2+} + 2Fe^{3+} + 8OH^- \rightarrow Fe_3O_4 + 4H_2O.$$

The produced MNPs (with an average diameter of 15 nm) possessed high crystallinity and super-paramagnetism (74.86 emu g^{-1} saturation magnetization). Fe_3O_4 NPs coated with $C_{12}H_{25}OSO_3Na$ were with uniform size and exhibited better dispersion, compared to uncoated.

Giri and co-authors synthesized MNPs using ferric iron ions obtained by treatment of tailing of iron ore industries [29]. The material containing ≈39.01% Fe was digested in HCl solution to produce $FeCl_3$ solution. Concentrated NH_4OH solution was added to produce $Fe(OH)_3$ that was washed, dried and dissolved in 50% HCl solution together with $FeCl_2 \cdot 4H_2O$ at $Fe^{3+} : Fe^{2+}$ molar ratio of 2:1. Then NaOH solution was added to reach pH 11, under continuous stirring, nitrogen (N_2) atmosphere and 70°C. Further, temperature was risen to 90°C, sodium dodecyl sulphonate was added to stabilize the formed MNPs. After cooling to ambient temperature, the produced MNPs were magnetically separated, washed with acetone and distilled water and sonicated. The dispersed MNPs (from 8.3 to 23.0 nm) were used in adsorption studies. They were found effective in removing anionic (Congo red) and cationic (methylene blue) dyes from their aqueous solutions with adsorption capacities of 70.4 and 172.4 mg g^{-1} for methylene blue and Congo red, correspondingly.

Kumar et al prepared MNPs using as a Fe source the waste from the iron ore processing plant [30]. The waste material contained 26.8% Fe_2O_3, 72.4% SiO_2 and 0.7% Al_2O_3. Metallic iron was added at the ratio of Fe to Fe_2O_3 content of tailings = 1:4 and the mixture was subjected to ball milling followed by leaching with HCl solution. Thus, chloride solution was produced that contained iron (III) and iron (II) at ratio of 2:1 M. Urea was added to the solution and its hydrolysis at 95°C released ammonia (NH_3) that alkalized the medium and black MNPs were formed in the suspension. After the suspension was cooled to room temperature, the NPs were removed by magnetic separation, washed and dried in a vacuum desiccator (at room temperature). The produced MNPs were coated with silver (Ag) nanoparticles by wet impregnation with aqueous silver acetate followed by washing and drying. The antibacterial activity of the prepared Ag–Fe_3O_4 nano-composite was studied against *Escherichia coli*. Silver coated MNPs possessed antibacterial activity. Silver NPs anchored to the Fe_3O_4 can be easily separated from the water by a suitable magnet in order to be reused. Thus, waste can be converted into useful resource and the produced product can be applied in water treatment.

Suh et al started from a low-grade iron ore and prepared MNPs (with a purity of 99.8%) and a Mg-rich solution that were used as a nano-adsorbent and a coagulant for water treatment, correspondingly [31]. Aqueous HCl solution was used to leach the ore. After solid/liquid separation, 30% H_2O_2 was added to convert all iron available in the solution to Fe^{3+} ions. Impurities that passed to the PLS were removed by solvent extraction with tri-n-butyl phosphate as an extractant. Therefore, the amounts of Mg and Si that are able to inhibit the formation of MNPs, were reduced from 15.5 wt.% and 10.3 wt.% to less than 1.4 mg L^{-1} and 28.1 mg L^{-1}, respectively. As a result, the Fe content increased from 68.6 wt. % to 99.8 wt. %. This high-purity Fe^{3+} solution was used to synthesize 5-15 nm MNPs. The high-purity Fe^{3+} solution was mixed with ferrous solution (obtained by reducing one-third of the high-purity Fe^{3+} solution with sodium borohydride – $NaBH_4$ aqueous solution) in the ratio of 2:1 and the obtained mixture was added to NaOH solution. The following reactions took place at 40°C to produce MNPs:

$$\begin{gathered}
Fe^{2+} + 2OH^- \to Fe(OH)_2, \\
Fe^{3+} + 3OH^- \to Fe(OH)_3, \\
Fe(OH)_3 \to \alpha - FeOOH + H_2O, \\
Fe(OH)_2 + 2\alpha - FeOOH \to Fe_3O_4 + 2H_2O.
\end{gathered}$$

The synthesized NPs were washed with distilled water and separated by using a magnet. Thus, MNPs adsorbent can be produced in large quantities at low cost and at the same time the cost of iron-ore-wastewater treatment could be decreased.

Ren and co-authors [32] used ferrous sulphate heptahydrate ($FeSO_4 \cdot 7H_2O$, 92.45%) that is an industrial by-product from titanium dioxide production by sulphuric acid (H_2SO_4) method and pyrite (FeS_2, 75.62%) that is a by-product of mineral processing plants. Ferrous sulphate was reduced with pyrite under N_2 protection to produce porous MNPs (with particle size of 25–50 nm).

Iron ore tailings (containing 43.47% Fe, 7.99% Si, 9.07% Ca, 3.8% Mg, and 2.4% Al) were ball milled and leached in mixture of 5 M H_2SO_4 and 2 M NaCl at 85°C [33]. The use of H_2SO_4/NaCl hybrid lixiviant resulted in decreased Ca^{2+} ions impurity in PLS because of precipitation of gypsum. Then Fe^{3+} ions in the produced PLS were reduced by adding sodium thiosulfate pentahydrate ($Na_2S_2O_3 \cdot 5H_2O$), under N_2 atmosphere, in such stoichiometric amount to obtain and maintain the $Fe^{3+}/Fe^{2+} = 2$. Further NH_4OH was added to reach pH=9.5, under N_2 atmosphere at room temperature. Greenish black precipitate was formed that was heated at 85°C and then the magnetic precipitate was gathered with a magnet, washed with distilled water and ethanol, and dried at 44°C. The XRD and ICP-OES analyses showed that the produced magnetite nanoparticles (with an average diameter of 19±3 nm) were pure (impurities $< 3\%$). The VSM analysis showed that the powder behaved as ferromagnetic at room temperature with a saturation magnetization of 63.27 emu g^{-1}. The proposed reduction-precipitation method is suitable and economic for producing MNPs when low amount of iron ions present in the tailings ($< 25\%$).

Microorganisms have also been studied for their ability to produce iron oxide NPs from mining waste. The bacterium *Rhodococcuserythropolis* ATCC 4277 was used in stirred tank reactor to extract residual iron from rhomboclase (found in coal tailings) and to transform it into magnetic nanoparticles [34]. The prepared NPs were composed of β-Fe_2O_3 and α-Fe_2O_3. The proposed process is environment-friendly and sustainable.

2.1.2. Other iron-based materials. Two organic-inorganic hybrid materials with magnetic properties were synthesized, using as precursors the iron ions obtained from Fe ore mining tailings [35]. The first precursor material consisted mainly of ferric sulphate. It was from iron mine tailings of a company. The second precursor resulted from the acid extraction of iron mine sludge gathered from the Doce River watercourse near the Fundão dam in Mariana, after its rupture in 2015. The hybrid materials were produced in the following way: $CoCl_2 \cdot 6H_2O$ and waste iron salts were dissolved in natural organic material (NOM)-rich water. Then the solution was alkalized to pH 9 with 1 M NaOH solution, the precipitate formed was washed and dried. SEM and TEM images pointed at the formation of nanostructures, while XRD analyses disclosed formation of the cobalt ferrite phase ($CoFe_2O_4$). The hybrids obtained (NOM-$CoFe_2O_4$) exhibited conversion rate of 99% of nitrophenol in short times (1-2 min). They also showed high performance in the adsorption of PAHs, achieving removals in the range of 75–80%.

Other study has presented synthesis of manganese ferrite ($MnFe_2O_4$) from a low-grade mining waste bearing both iron and manganese [36]. Initially the material was heated at 700°C and then leached in H_2SO_4 medium. Further, the leachate was purified and its composition adjusted to reach the Fe : Mn molar ratio of 2:1. The $MnFe_2O_4$ synthesis was achieved through co-precipitation from the solution at temperature of 90°C. The obtained nano-sized particles (45 nm) possessed a saturation magnetization of 51.03 emu g^{-1} and are candidates for energy storage devices.

Yao et al synthesized interconnected α-Fe_2O_3 nanoparticles using tin ore tailings as Fe source [37]. The ore tailings (containing 20.9% Fe) were leached in 1.5 mol L^{-1} H_2SO_4 at 70°C, the liquid-solid ratio of 4:1 (mL:g) for 90 min. Further, sodium carbonate (Na_2CO_3), NaOH, and NH_4OH solutions were added to the equal volumes of the PLS to precipitate iron hydroxide. The precipitate was washed and calcinated at 800 ^oC to obtain α-Fe_2O_3 nanoparticles. The α-Fe_2O_3 nanostructures synthesized by using $NaCO_3$ as precipitating reagent showed the best lithium storage performance with a reversible discharge capacity of 1146 mAh g^{-1} at 0.5 A g^{-1} after 300 cycles and stable discharge capacity of 377 mAh g^{-1} at a high current density of 4 A g^{-1}. The obtained results point at the possibility to use the ore tailings to produce high-value products.

Natural pyrite NPs were prepared by grinding pyrite taken from real mine waste to micro particles (< 50 μm), washing them with 0.5 M HNO_3 and additional grinding in ceramic mortar followed by ball milling in a planetary ball mill.

Thus produced NPs were rinsed with a mixture of ethanol and deionized water (50/50) and dried at 105°C [38]. The obtained NPs were studied for their ability to function as a catalyst for the activation of peroxymonosulfate (PMS) and peroxydisulfate (PDS) to oxidize tetracycline (TTC). A degradation of 98.3% and mineralization up to 46% of TTC were achieved using the produced pyrite catalyst. In addition, biochemical and histopathological assays pointed that nephrotoxicity and hepatotoxicity effect of TTC were decreased by 90% and 85% respectively. The pyrite NPs catalyst was used in four consecutive cycles with no significant decrease in process efficiency (<3% decrease in TTC removal). Furthermore, it was found that the pyrite presence in the water had not any significant toxic effects. The generalized route used for the preparation of MNP from mining waste is presented in figure 1.

2.2. Nanoparticles based on other metals

Mining waste material contains other valuable elements besides iron and have to be considered for their utilization in the NPs preparation. However, until our days no many efforts appeared in this direction.

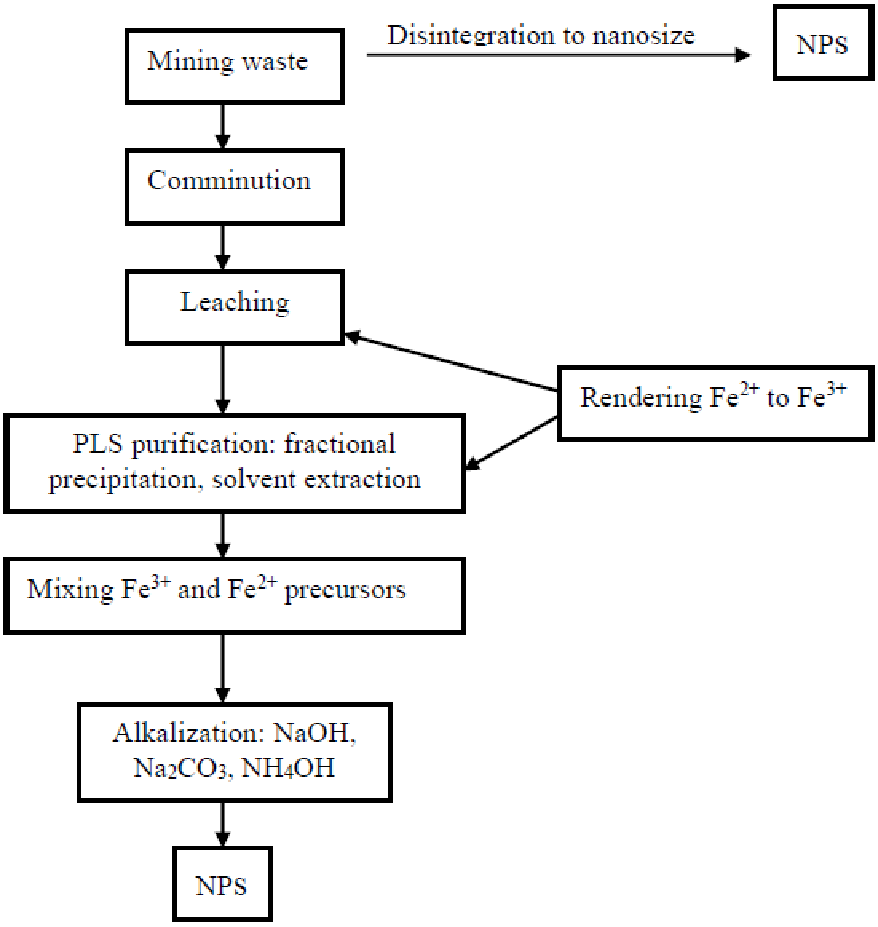

Figure 1. Generalized route for preparation of magnetic nanoparticles from mining waste.

Wong-Pinto et al utilized a real effluent produced by the leaching of sulfide ore tailings as a copper source to synthesize copper nanoparticles (CuNPs) using the non-pathogenic bacteria *Pseudomonasstutzeri* DSM 5190 as a bio-reducing agent [21]. In order to extract the Cu from the chalcopyrite-bearing tailings, they were treated with H_2SO_4 solution (120 g L^{-1}) in presence of sodium nitrate (1 g L^{-1}) that acted as an oxidizing reagent able to enhance Cu dissolution. A copper recovery of 50% was achieved in 8 h. Further, the PLS was purified by solvent extraction (using Acorga PT5050 diluted with Escaid 110) and then Cu was stripped with H_2SO_4 solution (120 g L^{-1}). The obtained solution was used as a precursor for CuNPs synthesis after raising its pH to 4 by addition of NaOH solution. Then, pellets of cultured *Pseudomonasstutzeri* DSM 5190 were added to the Cu-bearing solution. Some of the produced CuNPs (1–2 nm) were attached to the pellets of the biomass, other were left in the solution which after drying produced Na_2SO_4 – CuNPs mixture. The obtained products are intermediate. Different techniques have been proposed to separate CuNPs from the biomass (such as washing-vacuum filtration, density gradient centrifugation, sonication), which are relatively cheap and clean methods.

Recently a study appeared on the synthesis of selenium NPs (SeNPs) using mining waste that contained 6.11% Se, 4.97% Sb, 4.69% Pb, 4.12% Ag, 3.61% Cu and 70.01% barium sulphate ($BaSO_4$) [39]. In order to prepare pure solution for SeNPs synthesis the following stages were taken: (a) gravity separation to remove $BaSO_4$, (b) Leaching of the obtained concentrate by 3M nitric acid (HNO_3), (c) Chloride solution addition to precipitate Ag and Pb as insoluble salts, and (d) removal of other impurities such as tellurium, strontium and arsenic by different reagents addition, followed by solid/liquid separation. The purified solution was utilized as a precursor for the green synthesis of SeNPs using different fruit extracts with the orange extract being found to be the most efficient reducing and stabilizing reagent leading to the formation of stable SeNPs with particle size between 70 and 80 nm.

3. Nanoparticles from acid mine drainage

Recently various efforts have been done to handle AMD with the aim not only to decrease the content of hazardous elements that present in it but also to produce valuable minerals and metals by the AMD treatment. In this line, efforts to produce NPs have their place. Studies on the synthesis of iron based materials are prevailing but also other metals and minerals are aimed at.

3.1. Iron based materials

Efforts to use AMD to synthesize MNPs started also 15-17 years ago. One of the pioneering works was that of Wei and Viadero [27]. They recovered ferric iron from AMD pumped out from abandoned underground coal mines. Hydrogen peroxide was added to the raw AMD to oxidize the eventually available Fe^{2+} to Fe^{3+}. Then the AMD pH value was raised from the natural 2.6 to 3.5–4.0 by addition of 4 M NaOH solution. At this iron was precipitated as ferric hydroxide/oxyhydroxide. At pH 3.5 other metals remained in the solution. The precipitate was separated from AMD by centrifugation. The ferric precipitate was resolubilized and used as a ferric iron source. Reagent-grade $FeSO_4 \cdot 7H_2O$ was the ferrous iron source. Solution containing $Fe^{3+} : Fe^{2+} = 2 : 1$ was prepared under a $N_{2(g)}$ atmosphere to prevent oxidation and mixed for a certain time to remove the dissolved oxygen. Further, pH was risen to 9.5 by addition of 6.4 M NH_4OH solution. NPs were allowed to grow for 30 min, under N_2 atmosphere. The black precipitate (magnetite NPs with size of 10-15 nm) was separated from solution with the aid of an external magnetic field and washed. The prepared MNPs were of the same quality as the MNPs prepared using chemicals (pure iron salts) under the similar conditions.

Cheng et al studied microbial fuel cells that can be used to treat AMD and generate electricity [40]. The dissolved oxygen reacts with Fe^{2+} in AMD and iron oxide precipitates are produced that at frying are transformed to goethite (α-FeOOH) NPs with size in the range from 120 to 700 nm. The size of the produced NPs could be controlled by changing the conditions in the fuel cell – initial Fe^{2+} concentration (50–1000 mg L^{-1}), pH (4–7.5) and the cell current density (0.04–0.12 mA cm^{-2}).

Kefeni et al initially optimized the conditions for synthesis of MNPs from analytical grade chemicals at low pH and temperature and then applied the optimized conditions to treat real AMD with the aim to produce valuable commercial NPs [20]. They have proved that it is possible to synthesize Fe_3O_4 and $CoFe_2O_4$ from their corresponding binary salts. However, the direct application of the same conditions to both simulated and real AMD did not result in the MNPs formation. The reason was the presence of many other cations that can hinder that process. Beside iron oxides, Mn_3O_4, MnO_2 and ZnO were formed from real AMD. It is found that in order to produce MNPs from AMD higher pH and heat are needed in comparison with the model binary solutions. The study showed that $NH_4OH_{(aq)}$ was better alkalizing reagent than NaOH solution. It is proved that if the AMD is treated with MNPs the formation of ferrites is accelerated which resulted in an increased magnetic moment of ferrite sludge produced.

A study was conducted with the aim to recover Fe^{2+} and Fe^{3+} from Fe^{2+} rich acidic mine water that resulted from coal mining and washing processes, and to use the recovered Fe^{2+} and Fe^{3+} sludge as precursor for magnetite synthesis [11]. Only real AMD and soda ash were used. A sequential and fractional precipitation procedure was used to recover different Fe-species. In order to precipitate Fe^{3+} the pH value of the AMD was raised by Na_2CO_3 addition to pH$\geq$4.5 and to obtain Fe^{2+} the pH was increased to pH$\geq$8.3. Afterwards, the two recovered and collected sludges were used to synthesize magnetite. The reaction can be described as it follows:

$$Fe^{2+}_{(aq)} + 2Fe^{3+}_{(aq)} + 8OH^{-}_{(aq)} \rightarrow Fe_3O_4 + 4H_2O.$$

The formed magnetite (with a purity of 28%) was separated by centrifuging. The optimum conditions for the recovery of MNPs were mol ratio of Fe^{3+} / Fe^{2+}=2:1, pH≥10 and temperature ranging from 25 to 100°C.

Moreira et al prepared acicular goethite nanoparticles from AMD and studied their ability to adsorb arsenate, phosphate and humic acids [41]. The AMD was collected from a coal mine. It was treated using the following steps (the procedure is similar to that used at industrial scale to treat AMD): a) pre-neutralization by lime ($Ca(OH)_2$) addition to pH 2.7 to precipitate selectively aluminium hydroxides and $CaSO_4$, b) addition of NaOH to pH 3.2 to precipitate acicular goethite nanoparticles (AGNs). The AGNs were washed, filtered, dried at 90^{o}C for 5 h and stored. The obtained AGNs were similar in composition to the product derived at industrial scale at treatment of that AMD. The size of the AGNs was 23 nm, the material specific surface area was 102 m^2 g^{-1}. The AGNs adsorbed humic acid (37.30 mg C g^{-1}), arsenate (19.91 mg As(V) g^{-1}) and (12.98 mg PO_4^{3-} g^{-1}).

Further, a study has been carried out with the aim to explore the use of AMD as a source of Fe^{3+} ions as a precursor for synthesis of iron NPs and use of the produced NPs to remove pollutants from the same AMD [14]. A coal mine AMD (containing 4219.14 mg L^{-1} iron and 21,317.79 mg L^{-1} sulphate as the predominant anion) was used as feedstock. Initially the ferrous ion that present in the mine water was converted to ferric ion by addition of hydrogen peroxide solution:

$$2Fe^{2+} + H_2O_{2(aq)} + 2H^{+}_{(aq)} \rightarrow 2Fe^{3+} + 2H_2O_{(l)}.$$

In order to remove dissolved oxygen from the thus treated AMD, nitrogen gas was bubbled. Iron(III) ions that present in the mine water were reduced at room temperature using 0.5 M $NaBH_4$ solution to produce the iron nanoparticles.

$$4Fe^{3+} + 3BH_4^- + 9H_2O \rightarrow 4FeO + 3H_2BO_3^- + 12H^+ + 6H_2.$$

The synthesized black particles were separated from the mixture by using a strong external magnet, washed and dried. Their size was 31.8 nm and BET surface area was 88±3.16 m^2g^{-1}. For comparison iron NPs were synthesized under the similar conditions from pure chemicals as precursors. Their size and BET surface area were 28.05 nm and 91±3.08 mm^2g^{-1} correspondingly. The morphology of NPs prepared by starting from the different precursors was the same. The NPs synthesized by using AMD have been applied to remove toxic elements that present in the raw AMD. An average removal efficiency of 75% has been achieved due to combination of the different properties of the produced NPs, namely chemical stability, high redox potential and specific surface area as well as the presence of easily accessible adsorption sites. The main reactions leading to the pollutants removal have been identified as adsorption, co-precipitation and reduction.

Another study has used plant extracts to recover iron NPs from AMD [42]. Real wastewater from an industrial iron-ore processing company was used. Extracts of different plants were added to the wastewater at ratio of 1:1 v/v (determined as optimal in preliminary experiments) and temperature and contact time were varied. The precipitates formed were dried and annealed. Their analyses disclosed presence of maghemite-C (Fe_2O_3) and magnetite ($FeFe_2O_4$) nanoparticles. Best results at room temperature have been obtained when *Eucalyptus globulus* extract was used. In addition, the quality of treated mine water was improved and thus it was made reusable for other purposes.

Real AMD from a coal mine was used to synthesize goethite, hematite, and magnetite NPs [43]. Recovery of Fe^{3+} sludge and recovery of Fe^{2+} sludge was achieved by selective precipitation. The pH of the AMD was increased from 2 to 4.5 by addition of 10% Na_2CO_3 solution to obtain Fe^{3+} rich precipitates / sludge. The filtrate from the sludge / water separation was used for ferrous (Fe^{2+}) sludge production by raising the pH from 4.5 to $\geq$ 8.5 via addition of 10% NaOH solution. For goethite synthesis the Fe^{3+} rich slurry was heated at 80°C and then dried at room temperature for 24 h. For hematite synthesis the Fe^{3+} rich slurry was heated at 700°C and then cooled to room temperature. Magnetite nanoparticles were synthesized by mixing the preliminary obtained Fe^{3+} and Fe^{2+} sludge at 2:1 M ratio and adding NaOH solution to reach pH > 9 under oxygen-free environment achieved by N_2 gas bubbling into the reactor. High purity (>99%, =100% for goethite) has been observed for the recovered Fe-species, which indicates that they are suitable for industrial applications.

A recent study has applied hydrazine as reductant in order to produce iron nanoparticles using iron-rich AMD solution as a ferric iron source [44]. In order to prepare NPs 0.9 M hydrazine solution was added to AMD sample (4492.1 mg L^{-1} iron, pH=2.14) from a coal mine under stirring at a temperature of 70°C. A brownish yellow precipitate was formed that was identified by the XRD analysis as goethite. The SEM images of the iron nanoparticles revealed spherical morphology. The HRTEM analysis showed nanoparticles with size 8.66±0.58 nm and the XRF analysis results revealed that the samples were very rich in iron. It is concluded that Fe-rich AMD is a very good substitute material for commercial reagent grade salts for synthesizing iron NPs.

Another recent study proposed preparation of stabilized iron NPs from AMD applying rooibos tea extract as reagent used to reduce Fe^{2+}/Fe^{3+} to zero-valent Fe [45]. Ambient temperature (~25°C), a rooibos tea extract dosage of 5 g L^{-1}, a pH of 6, and 6 h of reaction time are found as optimal conditions. The average particle size was 36 nm, as determined by TEM analysis and the NPs were stabilized by tea polyphenols that partially coated the surface of the nano-iron. When the synthesized iron NPs were used as a Fenton like catalyst for the degradation of textile dye (orange II sodium salt), 94% removal efficiency was achieved in only 30 min.

3.2. Copper based materials

Schaffie and Hosseini proposed a biosynthesis of semiconductor copper sulfide nanoparticles from mine wastewaters with the aid of *Fusarium oxysporum* fungus [18]. Study was conducted with wastewater collected from a copper mine. The wastewater contained 56.75 mg L^{-1} Cu and its pH was 5.2. The bio-reduction of Cu ions occurred at 30°C for 96 h. The analysis of the separated and washed nanoparticles revealed that they possessed a covelite composition and the particle size was in the range of 10–40 nm. For comparative purpose NPs were synthesized also using 10^{-3} M $CuSO_4$ under the same conditions as when AMD was used. Analyses pointed that the properties of the NPs produced from AMD were the same as the properties of the NPs synthesized from the pure $CuSO_4$ solution.

Crane and Sapsford produced Cu nanoparticles from AMD using nanoscale zerovalent iron (nZVI) as a selective reducing reagent [16]. The AMD used was collected from abandoned open pit Cu-Pb-Zn mine. Its pH was 2.67 and the copper concentration – 45.41 mg L^{-1}. The used nZVI was prepared from $FeSO_4 \cdot 7H_2O$ by addition of 4 M NaOH solution. Two types of batch experiments were carried out – with unbuffered (pH 2.67 at t = 0) and pH buffered (pH < 3.1) AMD that was contacted with nZVI (with concentrations in the range of 0.1 – 2.0 g L^{-1}). It is found that addition of nZVI at concentrations $\geq$ 1 g L^{-1} to the unbuffered AMD lead to rapid and nearly total removal of Cu, Al and Cd from the water solution (> 99.9% removal within 1 h) through cementation (for Cu), precipitation and sorption to iron corrosion products (for Al and Cd). Other metals that present in the AMD were not immobilized. When buffered AMD was used Cu was selectively precipitated at addition of nZVI. The maximum removal of Cd and Al were only < 1.5% and < 0.5% correspondingly. Spherical nanoparticles (with diameter of 20–100 nm) were formed, containing up to 68 wt.% Cu, as revealed by HRTEM-EDS analysis.

The study showed that highly selective formation of Cu bearing nanoparticles from real AMD can be achieved by tuning the synthesis conditions.

3.3. Sulphides based materials
Below are presented some examples of metal sulphides NPs synthesis at contacting the AMD with sulphide ions produced by microorganisms.

Vitor et al studied the possibility to treat AMD at simultaneous bio-synthesis of zinc sulphide (ZnS) nanoparticles and ZnS / TiO_2 nanocomposites by using a combined process, developed by the members of this research group [19]. It consists of two consecutive steps – water neutralization in a calcite tailing column, and treatment of the neutralized water in an anaerobic sulphate reducing bioreactor. That process was planned to use locally available wastes and/or natural cheap materials, with the aim to develop as simple as possible, working at normal pressure and ambient temperature environmentally friendly and economically viable treatment of an AMD. The AMD used was collected from the region of an abandoned copper mine. The neutralizing column was filled with a mixture of small pieces of calcite tailing (from a marble stone cutting and polishing industry) and coarse sand, in a 1:2 (w/w) ratio. For the second stage the Upflow anaerobic packed-bed reactor was filled in with coarse sand. It was inoculated with sulphate reducing bacteria (SRB). The effluent from the bioreactor contained biologically generated sulphide. The biosynthesis of ZnS was realized by allowing the effluent from the biotreatment process to flow into a reaction vessel, containing a zinc sulphate solution. Composites were prepared by adding commercial titanium oxide (TiO_2) powder to the zinc solution. Over 90% of the zinc initially available in the AMD was removed as ZnS nanoparticles (with an average size in the range of 29 – 39 nm) or ZnS/TiO_2. Water going out of the system complied with legal irrigation requirements. The results obtained confirmed the possibility of coupling the synthesis of ZnS nanoparticles and nanocomposites with the AMD bioremediation.

Kumar and Pakshirajan studied the ability of biomass with SRB from an anaerobic rotating biological contactor to remove metals – (Cu(II), Cd(II), Ni(II), Fe(II), Pb(II), Mn(II) and Zn(II)) from simulated AMD while simultaneously rendering them in metal- sulphide nanoparticles [15]. The main mechanism of metal sulphide formation was the binding of metals to sulphide produced outside bacterial cell surface as a result of sulphate reduction by the bacteria. Heavy metals recovery by sulphide precipitation was over 70% for Cu and Pb. The recovery was a little bit lower for the other metals. Studies on the particle size distribution of the different NPs revealed that the size of NiS and ZnS nanoparticles was 15–17 nm, the size of CdS and CuS nanoparticles was 12–14 nm, the MnS NPs were 9–11 nm, while the size of FeS and PbS NPs was in the range 8–10 nm.

4. Conclusions and outlook
Studies carried out in recent 10-20 years have proved that:

(i) Mine tailings can be successfully used as iron source for producing different nanoparticles: magnetite, interconnected α-Fe_2O_3, ferrites and their composites, as well as copper and selenium nanoparticles – all with properties and prospective applications similar to the properties and applications of nanoparticles and composites fabricated from clean chemicals.

(ii) AMD can be utilized as an iron source for synthesizing magnetic, zerovalent iron, goethite and hematite nanoparticles, along with being a resource for copper and sulfide (copper, zinc, lead) nanoparticles and their nanocomposites. Besides NPs synthesis, remediation of the AMD is the other achieved positive result. The obtained materials showed ability to remove different pollutants from contaminated water.

The positive feature of the studies carried out is that most of them have used real waste material and AMD.

The following drawbacks could be pointed out: (i) The experiments are conducted at small laboratory scale, (ii) Most often solutions of strong acids are used as leaching reagents for mining waste, and strong alkaline solution (NaOH) is used as pH raising reagent in treating both the AMD and the PLS; (iii) Stabilization of the produced non-magnetic nanoparticles in different composites or on various carries (for example, clay, zeolite) is practically not studied, while it could contribute to easier separation and multiple use of those nanocomposites.

In short – production of nanoparticles and nanocomposites from mining waste and AMD seems promising environmentally friendly and feasible approach to minimize the negative impact of these waste streams and utilize them. However, there is still long way till their real implementation.

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References

[1] Radelović D, Mutić J, Marjanović P, Dordević T and Kašanin-Grubin M 2020 *Environ Sci. Pollut. Res.* **27** 6253–68 URL https://doi.org/10.1007/s11356-019-07348-4
[2] Mihailovski S, Mircovski V and Ilijovski Z 2021 *Rud. Geol. Naft. Zb.* **36** 121–29 URL https://doi.org/10.17794/rgn.2021.5.11
[3] Vallero D A and Blight G 2019 Chapter 6 - Mine Waste: A Brief Overview of Origins, Quantities, and Methods of Storage *Waste* ed Letcher T M and Vallero D A (Academic Press) pp 129–151 2nd ed URL https://doi.org/10.1016/B978-0-12-815060-3.00006-2
[4] Tayebi-Khorami M, Edraki M, Golder G and Golev A 2019 *Minerals* **9** 286 URL https://doi.org/10.3390/min9050286
[5] Kalisz S, Kibort K, Mioduska J, Lieder M and Małachowska A 2022 *Journal of Environmental Management* **304** 114239 URL https://doi.org/10.1016/j.jenvman.2021.114239
[6] Araya N, Kraslawski A and Cisternas L A 2020 *Journal of Cleaner Production* **263** 121555 URL https://doi.org/10.1016/j.jclepro.2020.121555
[7] Akinbile B J, Makhubela B C E and Ambushe A A 2021 *International Journal of Environmental Analytical Chemistry* 1–21 URL https://doi.org/10.1080/03067319.2021.1917557
[8] Zglinicki K, Szamałek K and Wołkowicz S 2021 *Minerals* **11** 352 URL https://doi.org/10.3390/min11040352
[9] Šajn R, Ristović I and Čeplak B 2022 *Minerals* **12** 547 URL http://doi.org/10.3390/min12050547
[10] Peiravi M, Dehghani F, Ackah L, Baharlouei A, Godbold J, Liu J, Mohanty M and Ghosh T A 2021 *Min. Metall. Explor.* **38** 1–26 URL https://doi.org/10.1007/s42461-020-00307-5
[11] Akinwekomi V, Maree J P, Zvinowanda C and Masindi V 2017 *J. Environ. Chem. Eng.* **5** 2699–2707 URL https://doi.org/10.1016/j.jece.2017.05.025
[12] Chen G, Ye Y, Yao N, Hu N, Zhang J and Huang Y 2021 *J. Clean. Prod.* **329** 129666 URL https://doi.org/10.1016/j.jclepro.2021.129666
[13] Ighalo J O, Kurniawan S B, Iwuozor K O, Aniagor C O, Ajala O J, Oba S N, Iwuchukwu F U, Ahmadi S and Igwegbe C A 2022 *Process Saf. Environ.* **157** 37–58 URL https://doi.org/10.1016/j.psep.2021.11.008
[14] Alegbe M J, Ayanda O S, Ndungu P, Nechaev A, Fatoba O O and Petrik L F 2019 *J. Environ. Chem. Eng.* **7** 103097 URL https://doi.org/10.1016/j.jece.2019.103097
[15] Kumar M and Pakshirajan K 2020 *Environ. Technol. Inno.* **17** 100542 URL https://doi.org/10.1016/j.eti.2019.100542
[16] Crane R A and Sapsford D J 2018 *J. Hazard. Mater.* **347** 252–265 URL https://doi.org/10.1016/j.jhazmat.2017.12.014

[17] Chen L X, Hu M, Huang L N, Hua Z S, Kuang J L, Li S J and Shu W S 2015 *J. ISME* **9** 1579–1592 URL https://doi.org/10.1038/ismej.2014.245
[18] Schaffie M and Hosseini M R 2014 *J. Environ. Chem. Eng.* **2** 386–391 URL https://doi.org/10.1016/j.jece.2014.01.006
[19] Vitor G, Palma T C, Vieira B, Lourenço J P, Barros R J and Costa M C 2015 *Miner. Eng.* **75** 85–93 URL https://doi.org/10.1016/j.mineng.2014.12.003
[20] Kefeni K K, Msagati T M and Mamba B B 2015 *Chem. Eng. J.* **276** 222–231 URL https://doi.org/10.1016/j.cej.2015.04.066
[21] Wong-Pinto L S, Mercado A, Chong G, Salazar P and Ordóñez J I 2021 *J. Clean. Prod.* **315** 128107 URL https://doi.org/10.1016/j.jclepro.2021.128107
[22] Kumar M, Nandi M and Pakshirajan K 2021 *J. Environ.l Manage.* **278** 111555 URL https://doi.org/10.1016/j.jenvman.2020.111555
[23] Maharana M 2021 *Mater. Today - Proc.* **47**(2) 1490–95 URL https://doi.org/10.1016/j.matpr.2021.04.370
[24] Ramutshatsha-Makhwedzha D, Ndungu P G and Nomngongo P N 2022 *J. Iran. Chem. Soc.* **19** 2949–61 URL https://doi.org/10.1007/s13738-022-02506-x
[25] Saravanan A, Kumar P S, Karishma S, Vo D V N, Jeevanantham S, Yaashikaa P R and George C S 2021 *Chemosphere* **264** 128580 URL https://doi.org/10.1016/j.chemosphere.2020.128580
[26] Hu J, Lo I M C and Chen G 2004 *Water Sci. Technol.* **50** 139–146 URL https://doi.org/10.2166/wst.2004.0706
[27] Wei X and Viadero R C 2007 *Colloid Surface. A* **294** 280–286 URL https://doi.org/10.1016/j.colsurfa.2006.07.060
[28] Wu S, Sun A, Zhai F, Wang J, Xu W, Zhang Q and Vollinsky A A 2011 *Mater. Lett.* **65** 1882–84 URL https://doi.org/10.1016/j.matlet.2011.03.065
[29] Giri S K, Das N N and Pradhan G C 2011 *Colloid. Surface. A* **389**(1–3) 43–9 URL http://doi.org/10.1016/j.colsurfa.2011.08.052
[30] Kumar R, Sakthivel R, Behura R, Mishra B and Das D 2015 *J. Alloys Compd.* **645** 398–404 URL https://doi.org/10.1016/j.jallcom.2015.05.089
[31] Suh Y J, Do T M, Kil D S, Jang H D and Cho K 2015 *Kor. Chem. Eng. Res.* **53** 39–45 URL https://doi.org/10.9713/kcer.2015.53.1.39
[32] Ren G, Yang L, Zhang Z, Zhong B, Yang X and Wang X 2017 *J. Alloy. Compd.* **710** 875–79 URL https://doi.org/10.1016/j.jallcom.2017.03.337
[33] Darezereshki E, Darban A K, Abdollahy M and Jamshidi A 2018 *J. Alloy. Compd.* **749** 336–343 URL https://doi.org/10.1016/j.jallcom.2018.03.278
[34] Maass D, Valério A, Lourenço L A, de Oliveira D and Hotza D 2019 *Hydrometallurgy* **184** 199–205 URL https://doi.org/10.1016/j.hydromet.2019.01.010
[35] Cruz D R S, Silva I A A, Oliveira R V M, Buzinaro M A P, Costa B F O, Cunha G C and Romão L P C 2021 *Chem. Phys. Lett.* **771** 138482 URL https://doi.org/10.1016/j.cplett.2021.138482
[36] Eghbali R, Hazaveh P K and Rashchi Fand Ataie A 2021 *Mater. Sci. Eng. B* **269** 115177 URL https://doi.org/10.1016/j.mseb.2021.115177
[37] Yao J, Yang Y, Li Y, Jiang J, Xiao S and Yang J 2021 *J. Alloy. Compd.* **855** 157288 URL https://doi.org/10.1016/j.jallcom.2020.157288
[38] Rahimi F, van der Hoek J P, Royer S, Javid A, Mashayekh-Salehi A and Sani M J 2021 *J. Water Process Eng.* **40** 101808 URL https://doi.org/10.1016/j.jwpe.2020.101808
[39] Shirmehenji R, Javanshir S and Honarmand M 2021 *J. Clust. Sci.* **32** 1311–1323 URL https://doi.org/10.1007/s10876-020-01892-7
[40] Cheng S, Jang J H, Dempsey B A and Logan B E 2011 *Water Res.* **45**(1) 303–7 URL https://doi.org/10.1016/j.watres.2010.07.054
[41] Moreira R F P M, Vandresen S, Luiz D B, José H J and Puma G L 2017 *J. Environ. Chem. Eng.* **5** 652–59 URL https://doi.org/10.1016/j.jece.2016.12.018
[42] Razanamahandry L C, Nwanya A C, Akharame M O, Muhammad B U, Ntwampe S K O and Fosso-Kankeu E 2020 *Minerals* **10** 859 URL https://doi.org/10.3390/min10100859
[43] Akinwekomi V, Maree J P, Masindi V, Zvinowanda C, Osman M S, Foteinis S, Mpenyana-Monyatsi L and Chatzisymeon E 2020 *Miner. Eng.* **148** 106204 URL https://doi.org/10.1016/j.mineng.2020.106204
[44] Alegbe M J, Moronkola B A, Osundiya M O, Adekolurejo E, Ajewole B S and Petrik L F 2022 *Am. J. Chem.* **12**(2) 23–31 URL https://doi.org/10.5923/j.chemistry.20221202.01
[45] Kimpiab E, Kapiamba K F, Folifac L, Oyekola O and Petrik L 2022 *ACS Omega* **7** 24423–24431 URL https://doi.org/10.1021/acsomega.2c01846

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Influence of the natural content of mineral impurities and moisture on the manifestation of hazardous properties of coal seams

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Influence of the natural content of mineral impurities and moisture on the manifestation of hazardous properties of coal seams

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Abstract. It is not possible to determine the type of coal in terms of reducibility from thermal decomposition without access to air for volatile maters to dry ash-free mass, which provides establishing the ratio between oxygen content and other essential components of organic mass. The hazards of coal mine operations depend to a large extent on the ratio of the main components, both in organic matter and in mineral impurities. Methods for determining the yield of volatile maters make it impossible to assess the effect of the main components of organic matter and mineral impurities on the hazard characteristics of coal seams. The volatile maters index reflects only the sum of the thermal decomposition gases: hydrogen, methane, carbon monoxide and carbon dioxide without considering the ratio between them. The determination of the hazard properties of a seam in relation to metamorphic transformations factor should include a case-by-case examination of the relationship between the major components of fuel both the organic and mineral, including the moisture content, for each coal seams.

1. Introduction

All current Ukrainian regulations on safe mining [1–8] do not use indicators that directly characterize changes in the elemental composition of coals due to metamorphic processes. For this reason, the influence of coal elemental composition on hazard expression remains largely unknown [9, 10]. Changes in the elemental composition of organic (combustion) mass during geological processes are established for most coal seams in Donetsk and Lviv-Volyn basins when determining the consumer properties of coal [11, 12]. The organic (combustible) mass, which characterizes consumer qualities, undergoes preliminary preparation, which consists in enriching coal and removing external moisture from it.

All types of solid fuels contain, in addition to the organic (combustion) mass, a mixture of mineral substances. When the fuel is burned, its organic mass is removed as CO_2 and H_2O, and the mineral components undergo a series of transformations to form ash. Ash is an inorganic residue from the complete combustion of coal [13]. The purpose of enrichment is to reduce the yield of ash. Coal is typically enriched with more than 10 % ash.

External moisture is a part of the total moisture of the fuel that is removed when it is dried to an air-dry state. The "total moisture" term is determined as the total external moisture content and the total moisture content of the air-dry fuel. The term is used to describe the humidity of coal as a whole (humidity content of coal). When drying coal in the air, free moisture from the outer surface of the pieces and capillary moisture from open cracks and pores (external moisture) shall be removed. Capillary moisture of closed pores, adsorption and hydrate moisture remain in the dry coal. When drying crushed coal at 105°C, the capillary moisture and adsorption moisture is removed from the pores opened by grinding [13]. In order to properly evaluate the results of the coal analysis in order to establish its consumption characteristics, it is necessary to know the humidity of the sample in which the indicators are measured. To this end, the concept of "analytical sample moisture" has been introduced, i.e. a moisture content in a sample of less than 212 µm (0.2 mm).

From the analysis reviewed, it is clear that the indicators in the handbooks [11, 12] are not directly relevant to the hazard characteristics of coal seams in underground mining, given the methods used to define them. They characterize only one part of the dry ash-free organic (combustible) component of coal. The proportion of mineral impurities, taking into accounts the ash yield, may exceed 40% [11, 12] in some cases, which can certainly affect the hazards of coal seams.

2. Research procedure

The elemental composition of the organic (combustible) mass is determined without considering the moisture content on which the physico-mechanical and physico-chemical properties of coal mine miners largely depend. One of the main elements that can influence the hazard behaviour of miners is oxygen. It is present in both organic and mineral mass of fuels and is largely responsible for coal restorability.

The methodology is based on the fact that the consumer qualities of solid fuels are determined on the basis of analytical samples brought to an air-dry state (analytical state). The results, which are expressed in other fuel conditions are calculative. Recalculation is made on the basis of ash content, humidity and mineral mass [13].

In the present case, the formulae for conversion are(%):

- from a dry, ash-free state:

$$O^r = O_c \cdot \frac{100 - (W_t^r + A^r)}{100}, H^r = H_c \cdot \frac{100 - (W_t^r + A^r)}{100}; \tag{1}$$

- organic mass:

$$O^r = O_c \cdot \frac{100 - (W_t^r + MM^r)}{100}, H^r = H_c \cdot \frac{100 - (W_t^r + MM^r)}{100} \tag{2}$$

where O_c, H_c – oxygen and hydrogen content in the combusted mass, %; O_r, H_r – oxygen and hydrogen content for the operating condition of the fuel, %; W_t^r – total moisture for the operating condition of the fuel, %; A^r – ash content of the sample, %; MM^r – mineral mass for the working condition, %.

The total moisture for the working condition of the fuel for each coal seam is given in the references [11, 12]. There is also information on the ash content of the seam (A_s^r) and enriched (A_e^r) samples.

The calculation of oxygen content to the operating state of the fuel O^r according to equation (2) is difficult due to the lack of a reliable method for determining mineral impurities in coals [6].

For all coal seams listed in the guide [11], using data on the ash content of enriched (A_e^r) and seam (A_s^r) samples and the total moisture content (W_t^r), the oxygen content was calculated according to equation (1) for enriched (O_e^c) and seam (O_s^c) samples respectively. Similar calculations have been made for coal seams in the guide [12], but only for the sum of oxygen and nitrogen for enriched ($\sum O_e^c, N_e^c$) and formation ($\sum O_s^c, N_s^c$) samples respectively.

The influence of coal enrichment and analytical sampling on changes in oxygen content on the operating state of the fuel was determined by comparing the graphs for enriched (figure 1) and formation (figure 2) samples, respectively.

The enrichment process contributes to the removal of some mineral impurities, which improves the quality of coal consumption properties. The ideal hypothetical enrichment option is to remove almost all (100 %) mineral impurities. The bisectrics (2) of the coordinate grid (figure 1) correspond ($O_e^r = O_c$) to this case. The mutual location of the bisectress (2) and the average line (1), as well as the regression coefficient (0.93) and the free term (0.04) of equation (1) indicate that the mineral impurities residue after enrichment causes a relative decrease of oxygen content on average from 3 to 7.0 %. This relative decrease increases with the oxygen content of the combustible mass. At absolute value $O_e^r = 1.0$ %, the average relative oxygen value drops by 3 % and at $O_e^r = 15.0$ % – by 6.7 %. With an absolute oxygen content of [11] in the combusted mass of 0.3 to 14.6 % in most cases, the maximum absolute reduction for individual coal seams is in limits beetwin 0.02÷0.98 %. These figures are derived from the position of the bisectress (2), the average line (1) and the standard deviations of the individual data ($\sigma = 0.27\%$) from the average line under the “three sigma” rule (figure 1). This accuracy in the determination of oxygen content is quite satisfactory when the organic (combusted) mass element composition is determined to a dry, ash-free state in order to clarify the consumer properties of coals.

An entirely different error is obtained when the oxygen content is recalculated to conditions close to the mining (working r) conditions under which the hazard properties of coal seams occur. For this case, the trendline (1) is also characterized by a high correlation coefficient (0.98), but it is much further away from the bisectress (2) of the coordinate grid (figure 2). This follows from the values of the regression coefficient of equation 1 (0.81) and the absence of a free term.

The influence of the natural content of mineral impurities and total moisture on the relative

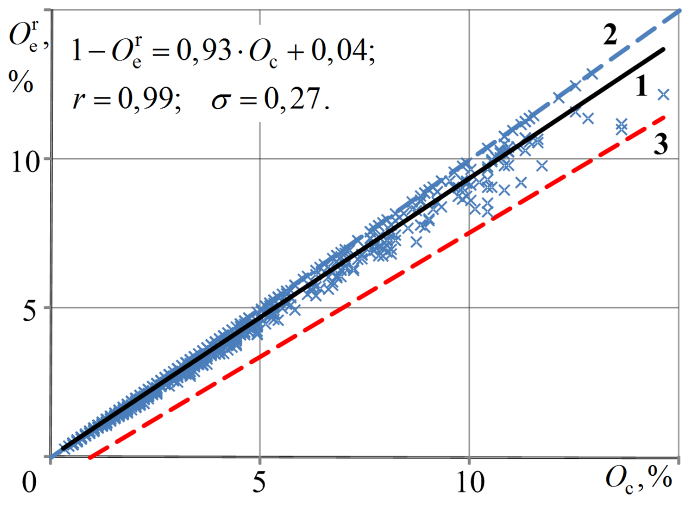

Figure 1. Oxygen Recalculation Results in combusted mass for working conditions of the fuel for enriched O_e^r samples of coal: 1 – the average trend lines; 2 – the bisectors of coordinate grids; 3 – a straight line defining the possible limit of maximum deviations of individual values from the trendlines (1) according to the “three sigma” rule; r, σ – correlation coefficients and standard deviations, respectively; × – experimental data [11] on the combustible mass of oxygen (O_c) converted to working condition according to [13].

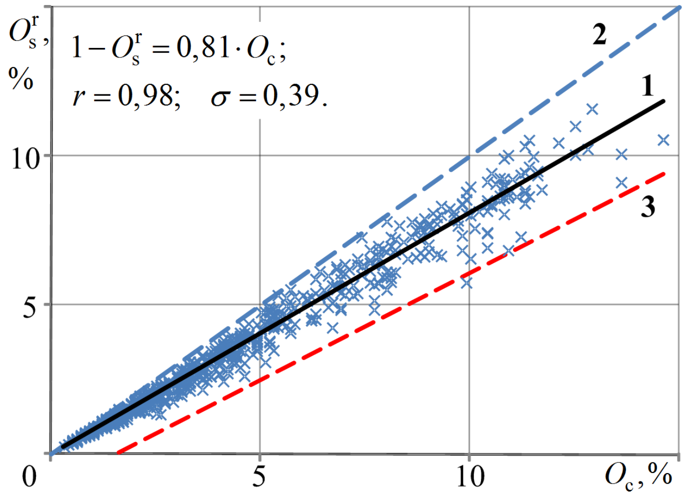

Figure 2. Oxygen Recalculation Results in combusted mass for working conditions of the fuel for seam O_s^r samples of coal: 1 – the average trend lines; 2 – the bisectors of coordinate grids; 3 – a straight line defining the possible limit of maximum deviations of individual values from the trendlines (1) according to the "three sigma" rule; r, σ – correlation coefficients and standard deviations, respectively; $\times$ – experimental data [11] on the combustible mass of oxygen (O_c) converted to working condition according to [13].

average decrease in oxygen content when converted to the working condition of coal is estimated on average to be 19.0 %. For the considered sample of coal seams (734), the absolute oxygen content of the combusted mass was in the range of 0.3 ÷ 14.6 %. The reduction in its content, when measured by the working condition, taking into account the actual discharge of ash and total moisture in the coals of each mine, is in absolute terms within the range of 0.00÷10.66 %. This follows from the resulting dependency (1) and related graphs (figure 2).

The ideal hypothetical enrichment option is to remove almost all (100 %) mineral impurities. The bisectrics (2) of the coordinate grid (figure 3) correspond ($H_e^r = H_c$) to this case. The mutual location of the bisectress (2) and the average line (1), as well as the regression coefficient (0.85) and the free term (0.09) of equation (1) indicate that the mineral impurities residue after enrichment causes a relative decrease of hydrogen content on average from 6 to 13.5 %. This relative decrease increases with the hydrogen content of the combustible mass.

At absolute value $H_e^r = 1.0$ %, the average relative hydrogen value drops by 6 % and at $H_e^r = 6.0$ % – by 13.5 %. With an absolute hydrogen content of in the combusted mass of 1.2 to 5.9 % in most cases, the maximum absolute reduction for individual coal seams is in limits beetwin 0.51 ÷ 1.71 %. These figures are derived from the position of the bisectress (2), the average line (1) and the standard deviations of the individual data ($\sigma = 0.15$ %) from the average line under the "three sigma" rule (figure 3). This accuracy in the determination of hydrogen content is quite satisfactory when the organic (combusted) mass element composition is determined to a dry, ash-free state in order to clarify the consumer properties of coals. An entirely different error is obtained when the hydrogen content is recalculated to conditions close to the mining (working r) conditions under which the hazard properties of coal seams occur. For this case, the trendline (1) is also characterized by a high correlation coefficient (0.95), but it is much further away from the bisectress (2) of the coordinate grid (figure 4). This follows from the values of the regression coefficient of equation 1 (0.68) and its free term (0.15).

The influence of the natural content of mineral impurities and total moisture on the relative average decrease in hydrogen content when converted to the working condition of coal is

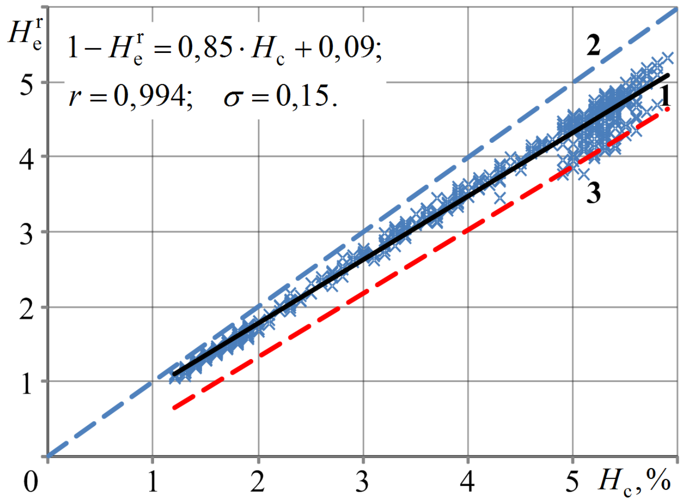

Figure 3. Hydrogen Recalculation Results in combusted mass for working conditions of the fuel for seam H_e^r samples of coal: 1 – the average trend lines; 2 – the bisectors of coordinate grids; 3 – a straight line defining the possible limit of maximum deviations of individual values from the trendlines (1) according to the "three sigma" rule; r, σ – correlation coefficients and standard deviations, respectively; × – experimental data [11] on the combustible mass of hydrogen (H_c) converted to working condition according to [13].

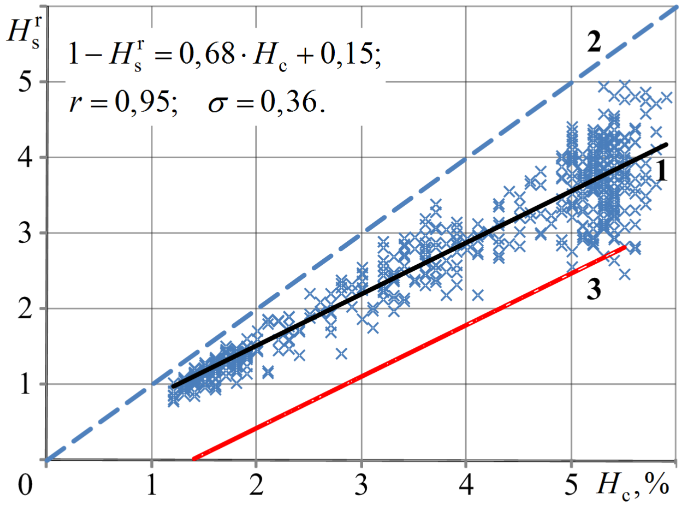

Figure 4. Hydrogen Recalculation Results in combusted mass for working conditions of the fuel for seam H_s^r samples of coal: 1 – the average trend lines; 2 – the bisectors of coordinate grids; 3 – a straight line defining the possible limit of maximum deviations of individual values from the trendlines (1) according to the "three sigma" rule; r, σ – correlation coefficients and standard deviations, respectively; × – experimental data [11] on the combustible mass of hydrogen (H_c) converted to working condition according to [13].

estimated from 17.0 to 29.5 %. For the considered sample of coal seams (557), the absolute hydrogen content of the combusted mass was in the range of 1.2÷5.9 %. The reduction in its content, when measured by the working condition, taking into account the actual discharge of ash and total moisture in the coals of each seam, is in absolute terms within the range of

1.25÷2.85 %. This follows from the resulting dependency (1) and related graphs (figure 4).

3. Discussion

A comparison of the graphs (figure 1, figure 3) and (figure 2, figure 4) shows that pre-enrichment and consideration of the elemental composition for dry ash-free coal samples predetermines a practical functional dependency from oxygen and hydrogen content. The removal of some random quantity of mineral impurities and completely external moisture has largely systematized the ratio between the oxygen and hydrogen content of the combustible mass and its reconsidered values by the working condition. However, the reference state of the samples taken for calculation does not correspond to the natural state of coal in the work area, as the actual mineral impurities and moisture content are not taken into account. For this reason, despite the almost functional dependancy (1) and the low standard deviations (figure 1 and figure 3), there is no reason to use the recalculated results for this case to predict the hazards of coal seams.

The presence of natural mineral impurities and total moisture in the seam's samples significantly influences the results of recalculation to working condition (figure 2 and figure 4). Primarily, this caused large deviations of individual values from the trend line (1), which makes it impossible to use the average oxygen and hydrogen values, recalculated by the working state of coal, to determine the hazards of a particular coal seam.

The total moisture content is one of the main indicators of the degree of coals' metamorphism, but it is generally not used in regulations to predict the hazards of miners [14]. The dependence of mineral impurities on the degree of metamorphic transformation is not generally established, but their presence in seam samples of coals of individual coal seams to be folowing a pattern [13]. This indicates that it is possible to individually characterise a coal seam by oxygen and hydrogen content, calculated by the working condition, taking into account the values of total moisture and total ash. The oxygen content of the organic (combustible) mass at a dry, ash-free state is an auxiliary indicator of one side of its metamorphic transformations. The carbon content in organic (combustible) mass is one of the main indicators of metamorphic transformation [14] because it functionally controls the sum of the other main components (oxygen, hydrogen, nitrogen, sulphur). The dependence of individual organic matter components on carbon is less clear. This applies in particular to the oxygen content of the organic (combustible) mass. This dependence is purely non-linear and is characterised by a high deterministic coefficient (R^2=0.87). The co-dependence of oxygen content with carbon, which is calculated as working-level ash output and total moisture content in enriched samples, is substantially lower.

For this case $r = -0.64$ and doubled the standard deviation of the individual values from the trend line ($\sigma = 2.21$). No specific relationship of oxygen content to carbon can be established in case of recovery from seam samples. It is characterized by a practical lack of correlation ($r = -0.34$) and a large standard deviation of the individual values ($\sigma = 2.39$). The reduction of mineral impurities ($A^r < 10.0$ %) after coal enrichment and their joint consideration with seam moisture has led to a significant reduction in the correlation between considered components when converted to working condition. The weakening of this dependence is caused by the partial enrichment of coals (the presence of a random residue of mineral impurities) and total moisture's presence, which are individually different for each mine. Consideration of the ratio between the components after they have been brought to working condition on the basis of the actual ash content and total humidity has led to an unpredictable redistribution of the influence of factors on oxygen content [15]. The natural accidental presence of mineral impurities and the different values of total moisture in the seam's samples have eliminated the monopolistic metamorphic ratio of oxygen in the organic, dry, ash-free mass to carbon. This resulted in a redistribution of the influence of factors on the components of O^r and C^r. Consideration of seam's samples with mineral inpurities and total moisture content has increased the number of influencing factors.

4. Conclusions

The formation and manifestation of dangerous properties of coal seams, judging by the requirements of current regulatory documents, are determined by the degree of metamorphic transformations of fossil coal. The use of indicators of mass ($V^d af$) and volume ($V_V^d af$) output of volatile substances, which are set for dry ashless combustible (organic) mass, excludes the possibility of analyzing the influence of moisture and mineral impurities on the manifestation of dangerous properties of coal seams. The use of these indicators for the prediction of dangerous properties of coal seams, instead of indicators for the working condition (r), can lead to errors in their determination by 50 and 45 %, respectively. The conducted research made it possible to reveal the important role of mineral impurities in the formation of dangerous properties of coal seams. This is caused both by the significant possible content of mineral impurities in fossil coal, and by the simultaneous presence of the main components that determine the dangerous properties of coal seams (carbon, hydrogen, sulfur, oxygen and moisture), both in the organic and mineral parts of fossil coal. The influence of the natural content of mineral impurities and total moisture on the relative average decrease in oxygen content when converted to the state of coal is estimated at 19.0 % on average.

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References

[1] 1979 *Rukovodstvo po bor'be s pyl'ju v ugol'nyh shahtah* (Moskva: Nedra)
[2] 2005 *SOU 10.1.00174088.011-2005: Pravyla vedennia girnychykh robit na plastakh, skhylnykh do gazodynamichnykh yavishch* (Kyiv, Ukraine: Ministry of Coal Industry)
[3] Janko S V and Tkachuk S P 1994 *Coal mine ventilation design guide* (Kyiv: Osnova)
[4] 2000 *KD 12.01.402-2000: Rukovodstvo po preduprezhdeniiu i tusheniiu endogennykh pozharov na ugolnykh shakhtakh Ukrainy* (Donetsk: NIIGD Respirator)
[5] 1987 *Instrukcija po prognozu i preduprezhdeniju vnezapnyh proryvov metana iz pochvy gornyh vyrabotok* (Makeevka: MakNII)
[6] 2009 *SOU-P 10.1.00174088.016:2009: Pravyla vyznachennia efektyvnosti vyperedzhalnoho zakhystu plastiv, skhylnykh do hazodynamichnykh yavyshch* (Kyiv: Minvuhleprom Ukrainy)
[7] 1983 *Katalog dinamicheskih razlomov gornyh porod na ugol'nyh shahtah* (Leningrad: Research Institute of Mining Geomechanics and Mine Surveying)
[8] Pashkovskiy P S, Kostenko V K, Zaslavskiy V P *et al.* 1997 *Endogennyye pozhary na ugol'nykh shakhtakh Donbassa. Preduprezhdeniye i tusheniye* (Donetsk: NIIGD)
[9] 2004 *SOU 10.1.0017-4088.011-2004: Degazacija ugol'nyh shaht. Trebovanija k sposobam i shemy degazacii* (Kyiv: Mintopjenergo Ukrainy)
[10] 2006 *Shemi ta sposobi keruvannja gazovidilennjam na viimkovih dil'nicjah vugil'nih shaht* (Kiev: Derzhavnij departament promislovoi bezpeki, ohoroni praci j girnichogo nagljadu)
[11] 1965 *Spravochnik po kachestvu i obogatimosti kamennyh uglej i antracitov Ukrainskoj SSR (Donbass v granicah USSR, L'vovsko-Volynskij bassejn). Harakteristika kachestva kamennyh uglej i antracitov Ukrainskoj SSR* (Moskva: Nedra)
[12] 1972 *Spravochnik po kachestvu kamennyh uglej i antracitov Doneckogo i L'vovsko-Volynskogo bassejnov* (Moskva: Nedra)
[13] Avgushevich I V, Sidoruk E I and Bronovec T M 2019 *Standartnye metody ispytaniya uglej. Klassifikacii uglej* (Moscow: Reklama master)
[14] Tarasov V, Antoshchenko M, Zakharova O, Zakharova A and Levadnyi O 2021 *E3S Web Conf.* **280** 6 URL https://doi.org/10.1051/e3sconf/202128008019
[15] Rudniev Y, Antoshchenko M, Filatieva E and Filatiev M 2022 *Coll.res.pap.nat.min.univ.* **69** 71–82 URL https://doi.org/10.33271/crpnmu/69.071

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Enhancement of the technology of caved ore drawing from the ore deposit footwall "triangle"

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Abstract. In mining iron ore, over 60% of underground mines at Kryvyi Rih iron ore basin apply a system with the bulk caving of ore and overlying rocks. However, when the deposit dip is 45-60 degrees, application of this mining system leads to losses of about 30-40% of the footwall ore. Available methods of the loss reduction result in an increase in production costs or a decrease in the iron content in the mined ore mass. After analyzing the mechanism of forming the figure of drawing, it is proposed to change its parameters without significant costs due to the use of an inclined plane and an overcompacted ore layer. The presented study enables stating that with an increase in the inclined plane angle from 45 to 75 degrees the draw crater radius increases from 2 to 7.5 m, and a decrease in the factor of first loosening of ore leads to an increase in the radius of the crater to 10 m. Thus, for the first time it is proved that a decrease in the first loosening factor leads to the increased semi-minor axis of the ellipsoid of drawing and the width of the active drawing area, which will reduce losses of caved ore when drawing it from the stoping block in the footwall area. It is established that in order to minimize losses and dilution of ore when using level mining systems, the drawpoint should be located in the block sill at a distance ensuring formation of the 20 to 25 m high ellipsoid of drawing. In case of an overcompacted 22 m thick ore layer, it is possible to significantly reduce ore losses from 14 to 10% and ore dilution from 16 to 9%, thereby enhancing ore mass extraction indices without additional costs.

1. Introduction

Kryvyi Rih iron ore deposit is a narrow strip of metamorphic rocks and it is an integral part of Kryvyi Rih-Kremenchuk deposit extending from south to north. The length of the ore deposits along the strike varies from 0.8 to 2.5 km due to different mining and geological conditions at different enterprises, [1–4].

Kryvyi Rih deposit consists of four suites: schist-amphibolite (K_0); lower arkose-phyllite (K_1); middle iron ore (K_2); upper schist (K_3) ones [1, 4–7]. The main productive thickness is (K_2) which embraces seven pairs of interchanging ore and schist layers [8–10].

The underground mines are working out the fourth, fifth and sixth ferruginous levels with rich iron ores (the average iron content is 60-63%) represented by various forms: stratal, layer-shaped, lenticular, pillar-like and nested, and in some cases their combinations within the mining block [11–15].

The geological cross-section of the deposit along the shaft of the KRYVORIZKA underground mine of the joint-stock company KRYVBASZALIZRUDKOM is given (figure 1).

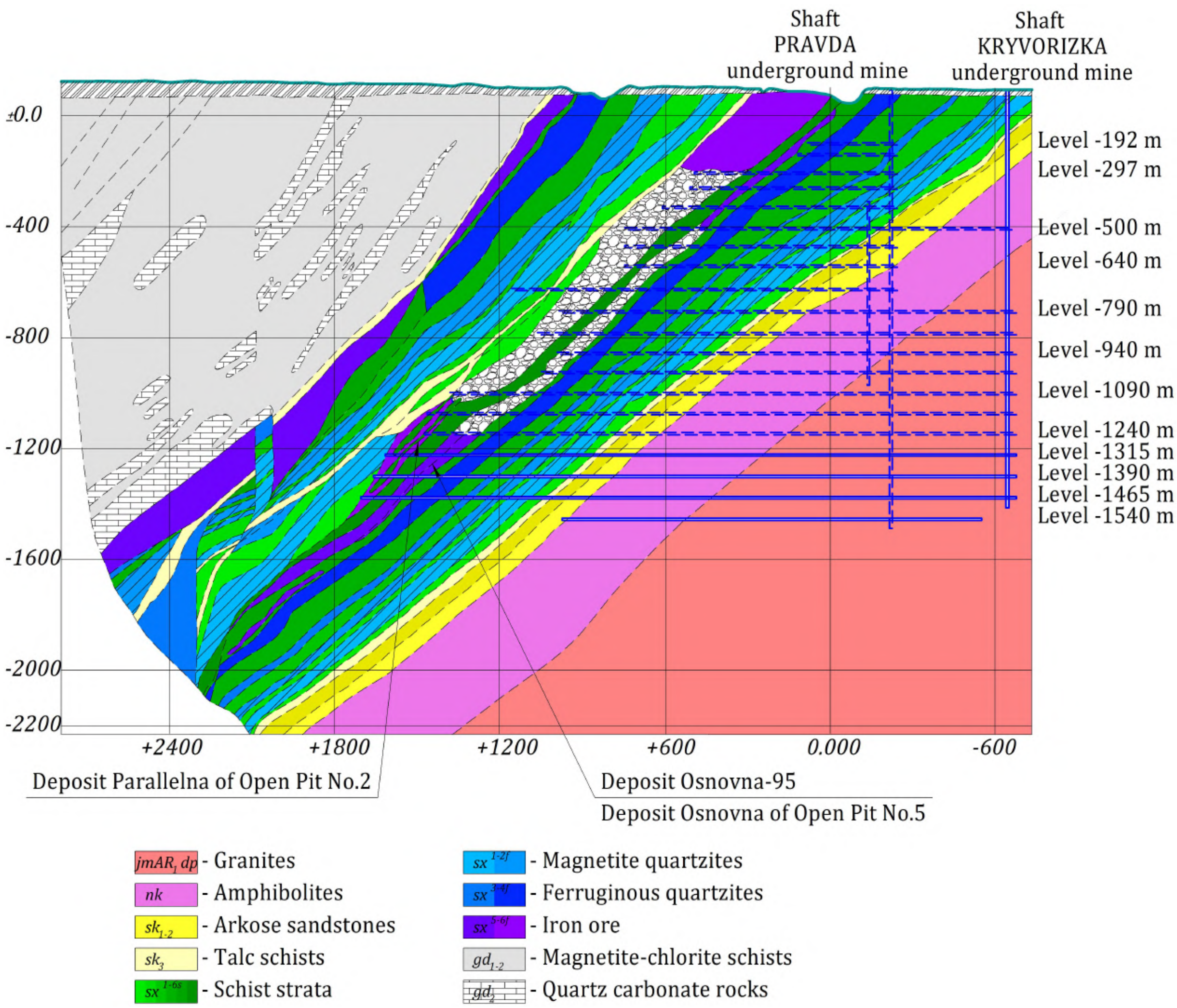

Figure 1. Geological cross-section of Kryvyi Rih iron ore basin along the shaft of the mine KRYVORIZKA, the JSC KRYVBASZALIZRUDKOM.

As is seen from figure 1, mining operations are carried out below level -1350 m. The analysis of mining enterprises shows that physical and mechanical properties, the shape of occurrence, the dip angle and stability change depending on the mining depth. In mining blocks there occur inclusions of waste rocks with the horizontal thickness of 0.5-12.0 m [16–20].

Rocks of the hanging wall and footwall are represented by strong, stable martite hornfels with ultimate compression strength of 100-130 MPa and goethite-hematite-martite hornfels with ultimate compression strength of 70-90 MPa. Physical properties of rocks are given in table 1.

As is seen from table 1, physical and mechanical properties of the rocks are wide in range. According to the geological data [1, 21, 22], the rich ores are of hematite composition and differ only in the number and proportion of mineral varieties [23–26].

Strength of iron ores declines with depth, and this deteriorates mining conditions. Thus,

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Table 1. Stratigraphic index and ultimate strength of rocks, Kryvyi Rih iron ore basin.

Rocks	Iron content in ore, %	Ultimate compression strength, MPa
Poor ores		
Carbonate-magnetite, PR_1Sx^{1f}	28-32	170-190
Amphibole-chlorite-magnetite, PR_1Sx^{2f}	28-34	150-170
Quartzite goethite-martite, PR_1Sx^{3f}	28-36	100-180
Martitic quartzite, silicate magnetite, PR_1Sx^{4f}	34-38	100-150
Quartzite hematite-martite, carbonate-magnetite, PR_1Sx^{7f}	28-34	100-130
Rich ores		
Martite, hematite-martite, hematite, PR_1Sx^{5-6f}	58-63	70-90
Schistous rocks		
Quartz-chlorite-biotite, PR_1Sx^{1s}	-	130-150
Quartz-sericite-chlorite, PR_1Sx^{2s}	-	90-110
Quartz-mica, silicate, PR_1Sx^{3-5s}	-	70-120
Colored quartzite with martite crystals, PR_1Sx^{6s}	-	90-130
Chlorite-amphibole-hematite, carbonate-magnetite-chlorite, PR_1Sx^{7s}	-	120-160

every 500 m of the depth increase reduces the gradient of the compression strength of rocks by 0.6–0.7, and for the central part it makes 0.9–1.0 [27–30].

When mining iron ore, over 60% of underground mines of Kryvyi Rih iron ore basin apply a system with the bulk caving of ore and overlying rocks [31–34].

These mining systems have the following disadvantages [35–38]: ore losses on the footwall (up to 30-50% of the total ore losses); ore dilution (by 3-5% more than standard); reduced content of the useful component in the mined ore mass.

When the deposit dip is 45-60 degrees, application of these mining systems results in about 30-40% of ore lost on the footwall [39–43]. Increased losses of ore during mining lead to an increase in the specific volume of mining and capital works, pre-term mining of levels [21].

In this regard, the scientific and technical task of studying and enhancing the technology of mining ore deposits by the underground method for Kryvyi Rih iron ore basin in the “triangle” of the footwall (in the “dead” area) when working out ore deposits with a dip of 45-60 degrees to minimize ore losses is topical.

2. Purpose

One of the solutions for this scientific and technical problem involves developing a method to reduce ore losses in the footwall “triangle” without increasing the cost of caved ore drawing.

The present work aims to study and enhance the technology of mining ore deposits by enhancing the mode of drawing, which will reduce ore losses on the footwall in underground mining at Kryvyi Rih iron ore basin.

To achieve this goal it is necessary to solve the following tasks:

(i) Analyzing iron ore mining practices and ways to reduce ore losses in the footwall influence area.

(ii) Conducting studies to reduce ore losses in the “dead” area of the ore deposit.

The idea behind the work is to use regularities of ore movement under an inclined plane when working out ore deposits with a 45-60 degrees dip by bulk caving systems.

3. Analysis of researches and publications

Caved ore drawing from blocks when using systems with the bulk caving of ore is one of the most important production processes. Depending on the accepted method of ore drawing, ore losses and dilution are calculated, and the main parameters of the mining system are determined. This is due to the fact that 30-45% of the caved ore reserves is drawn from a block under overlying rocks, while losses in the block make 14-16%, and ore dilution is 12-20% [44–48].

A significant number of publications are devoted to the issue of reducing losses and dilution of caved ore from the stoping block [49–53]. Scientists of Kryvyi Rih National University (Ukraine) have made a significant contribution concerning ore drawing under caved rocks [54–61]. The panel enclosed by vertical walls of the ore massif from four sides is more favorable in terms of drawing from blocks as such conditions increase extraction indicators.

According to studies, the following factors significantly impact extraction indices [31, 62, 63]:

- intensification of ore drawing under caved rocks;
- the distance between the axes of drawpoints;
- structural elements of the mining system.

It is proved that the optimal distance between the axes of drawpoints is 4-6 m when drawing ore using scraper winches or vibration equipment, and 8-12 m – when using self-propelled loading machines or underground excavators. This enables significant reduction of ore losses and dilution but increases costs for driving and maintaining workings.

The authors of [1, 6, 31, 54] argue that the distance between drawpoints is inversely proportional to the height of the sublevel and proportional to losses in ore drawing. Therefore, depending on the height of the sublevel, the ore deposit thickness and the dip angle, it is necessary to use the appropriate drawing mode: even, sequential, advance and others, thus allowing reduction of ore losses on: the stoping block sill; the footwall of the ore deposit.

However, when working out a block, a significant amount of broken ore remains in the footwall influence area, especially when using the bulk caving system in unstable rocks. When drawing ore under caved rocks, about 25-35% of the reserves remains in the footwall influence area, and when working out deposits in unstable rocks of the hanging wall, ore losses reach 50% [64–67].

Practices of mining ore deposits with a dip of over 75 degrees applying systems with the bulk caving of ore and country rocks show that ore losses in the footwall influence area are minimal and do not exceed 5-7%. However, the number of such deposits in Kryvyi Rih iron ore basin is less than 15-17% [68–70].

To reduce ore losses on the footwall when mining deposits with a dip of less than 60 degrees. the following technological solutions are applied (figure 2) [31, 32, 54, 64, 71]:

- working out the "triangle" of the footwall as the first stage (figure 2(a));
- extracting the "triangle" of the footwall as the second stage (figure 2(b));
- cutting waste rocks in the footwall (figure 2(c));
- creating an additional receiving level with the complete working out of the ore massif and a single compensation room (figure 2(d)).

When working out the "triangle" of the footwall as the first stage (figure 2(a)), a scraper drift is driven 10-20 m above the main receiving level in the footwall of the deposit. An additional working of the receiving level can be driven in both ore and rocks of the footwall with drawpoints on one side.

Disadvantages include:

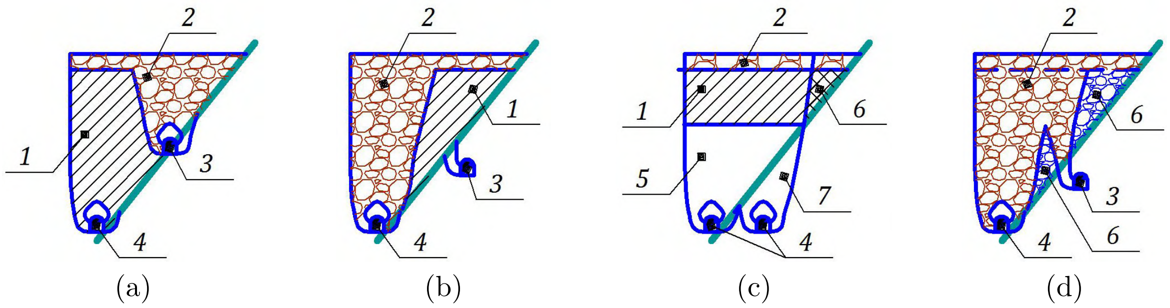


Figure 2. Methods of mining ore reserves in the footwall influence area: 1 – the ore massif; 2 – overlying rocks; 3 – the working of the additional receiving level; 4 – the delivery working of the main receiving level; 5 – the compensation room; 6 – losses of ore in the footwall influence area; 7 – cutting footwall rocks.

- significant costs for creation and maintenance of an additional receiving level;
- the specific volume of subsidiary development increased by 1.0-1.2 m/kt of reserves;
- significant dilution of ore with waste rocks as the height of the drawn ore layer increases.

The idea behind the method of mining the “triangle” of the footwall as the second stage (figure 2(b)) involves extraction of the main reserves of the panel with the help of delivery workings of the main receiving level, and the reserves of the footwall are broken and drawn afterwards. It should be noted that mining the “triangle” of the footwall in this way is carried out in difficult mining conditions, and in some cases it is hardly possible at all.

Disadvantages of this method of mining the footwall “triangle” include:

- increased unsafety of stoping; significant ore losses (up to 30-50%);
- a significant amount of subsidiary development (10-15 m/kt);
- low efficiency;
- high labor intensity and material costs.

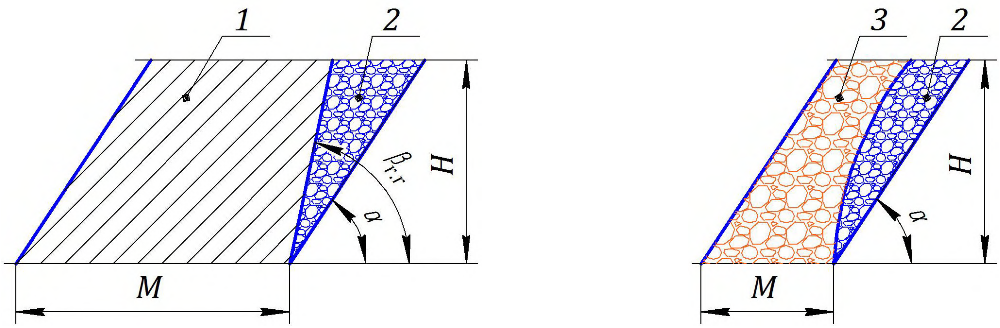
Extracting ore from the “triangle” of the footwall with cutting footwall waste rocks (selective mining) (figure 2(c)) involves creating a compensation room at the footwall on which the ore massif is broken. Due to movement of the massif, the broken ore is shifted from the footwall to the center at the level of undercutting. Thus, the broken ore enters the drawing area and is located on the footwall. The ore is drawn from the first row of drawpoints located in the footwall. After extracting the ore mass from the first row of drawpoints, drawing continues from the second row, and so on.

Advantages of this method consists in the following: on the footwall, the minimum amount of ore remains (up to 10%); driving additional workings in the footwall allows an increase in the size of the compensation room; a simplified scheme of preparatory-development operations is applied; a small part of the “triangle” at the top of the panel remains unmined; location of workings on the same level enhances occupational safety.

Disadvantages include the following: additional costs for creating a compensation room; a significant amount of additional work on driving workings in the footwall rocks; increased costs for maintaining additional workings; increased volume of mined waste rocks due to creation of the compensation room in the footwall.

To reduce ore losses on the footwall of the panels, the method of driving additional draw workings in footwall rocks is used (figure 2(d)). This scheme has found wide application in complete mining of the ore massif within the stoping block. The main requirements for application of this scheme of mining the “triangle” of the footwall are [54, 64]: relatively stable rocks of the hanging wall; medium thickness of ore deposits; the distance between the rows of drawpoints of additional receiving levels is determined such that ellipsoids of drawing touch waste rocks.

According to [54, 55], depending on the horizontal thickness of the ore deposit and the height of the caved layer, ore losses are formed in different ways (figure 3).



(a) (b)

Figure 3. Ore losses in the footwall influence: a) formation of a "triangle" of the footwall at an ore drawing angle of 75-81 degrees; b) formation of a "triangle" of the footwall parallel to the hanging wall; 1 – the ore massif; 2 – losses of ore in the footwall influence area; 3 – overlying rocks.

It is proved that when ore is being drawn, the figure of drawing is formed to the maximum height equal to the vertical thickness of the deposit. After reaching the contact with the inclined surface, the axis of the ellipsoid of drawing deviates and runs parallel to the footwall, forming a draw crater with the radius R_r.

4. Methods

A significant contribution to development of the theory of ore drawing has been made by Agoshkov et al [31], Malakhov et al [54], Korzh [64]. According to the results of their research, it is established that when caved ore is drawn from the mining block, the following figures are formed: ellipsoid of drawing, ellipsoid of loosening and draw crater (figure 4) [31, 54, 72, 73].

At the first stage, before the ellipsoid of drawing reaches the inclined surface, the figure of drawing is formed according to previous studies [1, 18, 54].

According to [31,32,54], the small and large semi-minor and semi-major axes of the ellipsoid of drawing are determined by empirical expressions (1) and (2) for fine and coarse ores respectively, m:

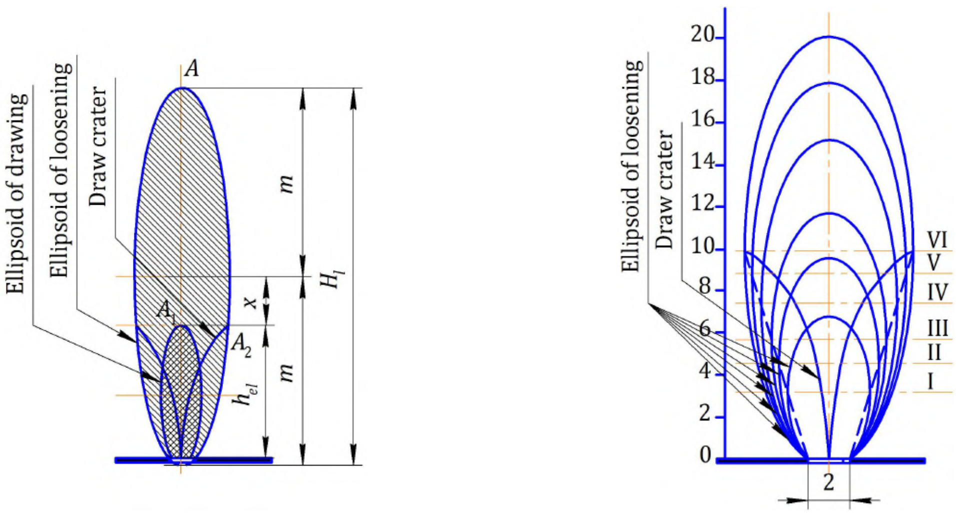
$$b = 0.007 \times h_{el} + 0.5 \times d, \qquad a = 0.512 \times h_{el}, \tag{1}$$

$$b = 0.1515 \times h_{el} + 0.5 \times d, \qquad a = 0.51 \times h_{el}, \tag{2}$$

where b is the semi-minor axis of the ellipsoid of drawing, m; h_{el} is the height of the caved ore layer (height of the ellipsoid of drawing), m; d is the diameter of the drawpoint, m; a is the semi-major axis of the ellipsoid of drawing, m.

The volume of the ellipsoid of drawing for ores with homogeneous loose properties is determined by the empirical formula, m^3

$$q = \left(\frac{h_{el}}{k_1} + k_2 \times d\right)^3, \tag{3}$$



(a) (b)

Figure 4. Formation of figures of drawing and loosening in drawing caved ore.

where k_1 is the tangent of the straight line inclination angle; k_2 is the empirical coefficient.

The volume of the ellipsoid of loosening Q_l is about fifteen times larger than that of the ellipsoid of drawing for loose non-compacted materials [21, 74, 75]. Therefore, the volume of the ellipsoid of loosening can be determined by the expression, m^3

$$Q_l = \mu_0 \times h_{el} \times b^2, \tag{4}$$

where μ_0 is the volume factor, assumed to be equal to 2.11.

Knowing the ratio of the volume of the ellipsoid of loosening to that of drawing, the latter can be determined according to the expression, m^3

$$q = \frac{Q_l}{n}, \tag{5}$$

where Q_l is the volume of the ellipsoid of loosening, m^3; n is the ratio of the volume of the ellipsoid of loosening Q_l to the volume of the ellipsoid of drawing q.

The ratio of the volume of the ellipsoid of loosening Q_l to that of the ellipsoid of drawing q that are formed during caved ore drawing depends on loose properties of the ore and is described by the dependency [33, 62, 71]

$$n = \frac{1}{1 - \dfrac{k_l}{\epsilon_{dyn} \times \epsilon_{kl} \times k_{l.is}}}, \tag{6}$$

where n is the angular caved ore drawing factor; k_l is the first loosening factor, unit fr.; ϵ_{dyn} is the dynamic component of subsequent loosening; ϵ_{kl} is the component of the subsequent loosening; $k_{l.is}$ is the subsequent loosening factor.

For magnetite ore, the indicators k_l and ϵ_{dyn}, are 1.0204 and 1.05 respectively [21, 33], the calculation results are given in table 2.

As is seen from table 2, when the caved ore first loosening factor decreases from 1.5 to 1.25, the ratio of the volume of the loosening figure to the volume of the drawing figure changes from 15.0 to 2.84.

Table 2. Volume to volume ratio for loosening and drawing figures.

First loosening factor, k_1	Subsequent loosening factor, ϵ_{kl}						
	1.50	1.55	1.60	1.65	1.70	1.75	1.80
1.50	15.00	10.33	8.00	6.60	5.67	5.00	4.50
1.45	10.23	7.88	6.49	5.56	4.90	4.41	4.03
1.40	7.76	6.37	5.45	4.81	4.32	3.95	3.65
1.35	6.25	5.35	4.71	4.23	3.86	3.57	3.33
1.30	5.23	4.60	4.14	3.78	3.49	3.26	3.07
1.25	4.50	4.04	3.69	3.41	3.19	3.00	2.84

In compacted ore, there is an intensive extinction of an increase in the volume of figures of loosening and ore drawing. Consequently, extinction of the increase in the volume of loosening figures is more intensive than that of the figure of drawing, as a result of which the ratio of their volumes decreases [76–79].

According to Korzh [33], the semi-minor axis of the ellipsoid of drawing is determined by the expression, m

$$b = r + m_0 \times \left(\frac{k_{exl} \times h_{el}}{h_0}\right)^n, \tag{7}$$

where r is the radius of the ore drawing flow, m; m_0 is the factor of increase in the semi-minor axis of the ellipsoid of drawing, m; k_{ext} is the factor of intensity extinction for the semi-minor axis increase; h_0 is the minimum height of the ellipsoid of drawing, m.

When drawing caved ore under overlying rocks [5, 21, 54], particle flow velocities throughout the entire period remain phase shifted by the constant value φ.

The trajectory of particles (the boundary of the ellipsoid of loosening) is determined by the expression [32]

$$y_1 = \sqrt{\varphi \times (x_1 + k) \times (1 - \epsilon^2)}, \tag{8}$$

where φ is the distance between points A0 and A1, m; y, x are coordinates of a point relative to the horizontal and vertical axes of the ellipsoid of loosening, m; k is the distance to which a piece of ore moves vertically, m; ϵ is eccentricity of the ellipsoid of loosening.

The second stage of ore drawing from a single drawpoint is characterized by the fact that with further caved ore drawing, parameters of the ellipsoid of drawing remain unchanged, and subsequent formation of the ellipsoid of drawing occurs parallel to the hanging wall, thus forming the draw crater.

It is proved that the normal ellipsoid of loosening is formed until the cutoff height $h = m \times \tan\alpha$ [31].

The draw crater radius R_r, which is equal to the vertical thickness of the ore body, is determined by the formula

$$R_r = \sqrt{(H_l - h) \times h \times (1 - \epsilon^2)}, \tag{9}$$

where H_l is the height of the ellipsoid of loosening, m; h is the height of the caved ore layer, m.

In [4, 33, 62, 64] it is argued that the curve forming the draw crater within the range $H_l - H$ moves parallel to the footwall. Thus, ore losses in the "triangle" of the deposit footwall are calculated by the expression, unit fractions

$$P = 1 - \frac{R_r}{M} - \frac{0.5 \times M \times \tan\alpha}{H} \times \left(1 - \frac{2 \times R_r}{M} + \frac{R_r^2}{M^2}\right), \tag{10}$$

where M is the horizontal thickness of the ore deposit, m; α is the dip angle of the ore deposit, degrees; H is the height of the caved ore, m.

5. Results

Laboratory studies enable establishing that the figure of drawing changes depending on the surface inclination angle. The results of studying changes in ore drawing angles depending on the surface inclination, distances between the drawpoint and the inclined surface and the width of the caved layer in the lower and upper parts of the "triangle" of the footwall are given in table 3.

Table 3. The angle of the caved ore movement under the inclined plane.

Ore deposit dip, degrees	Distance between a drawpoint and the inclined surface, m	Ore drawing angle, degrees, depending on on the caved layer width in the lower part of the mining block of the footwall "triangle"			
		4	6	8	10
45	10	57.2	66.0	72.4	76.4
	15	52.5	58.0	63.6	70.0
	20	50.5	54.1	58.0	62.3
50	10	63.5	73.5	75.0	78.0
	15	59.0	64.7	71.5	77.4
	20	56.5	60.5	65.3	70.0
55	10	70.5	75.7	77.0	78.3
	15	65.4	72.0	75.5	78.0
	20	62.5	67.0	72.5	77.3
60	10	77.2	77.5	78.0	78.5
	15	71.0	75.2	77.9	78.1
	20	68.1	73.2	76.6	77.6

Based on the results of the calculations performed, dependencies of the angle of the caved ore flow under the inclined plane on the angle of the ore deposit dip and the distance between a drawpoint and the inclined surface can be built (figure 5).

The graphs in figure 5 enable the conclusion that an increase in the ore deposit dip angle results in an increased angle of ore drawing under the inclined plane. Thus, an increase in the deposit dip from 45 to 60 degrees leads to increases of the angle of drawing from 57.2 to 77.2 at the distance of 10 m between a drawpoit and the inclined surface. When the distance between a drawpoint and the inclined surface increases from 10 to 20 m at the ore deposit dip of 60 degrees, the angle of ore drawing decreases from 77.2 to 68.1 degrees.

The dependency of the change in the angle of ore drawing under the inclined plane on the distance between a drawpoint and the inclined surface and the caved layer width in the lower part of the mining block of the "triangle" of the footwall shown in figure 6.

Figure 6 enables the conclusion that an increase in the distance between a drawpoint and the inclined surface from 10 to 20 m results in a decrease of the angle of caved ore drawing from 76.4 to 50.5 degrees. The graph shows that changing the caved layer in the lower part of the mining block of the "triangle" of the footwall and the distance between a drawpoint and the inclined surface approximate the angle of ore drawing to that of the deposit dip.

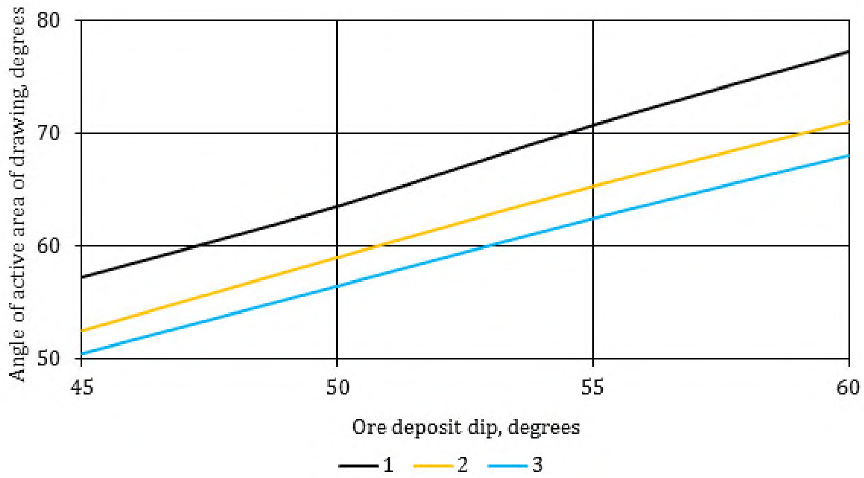


Figure 5. Dependency of the ore drawing angle on the ore deposit dip and the distance between a drawpoint and the inclined surface when the caved layer width at the lower part of the mining block is 4 m: 1, 2, 3 – the distance between a drawpoint and the inclined surface, 10, 15 and 20 m respectively.

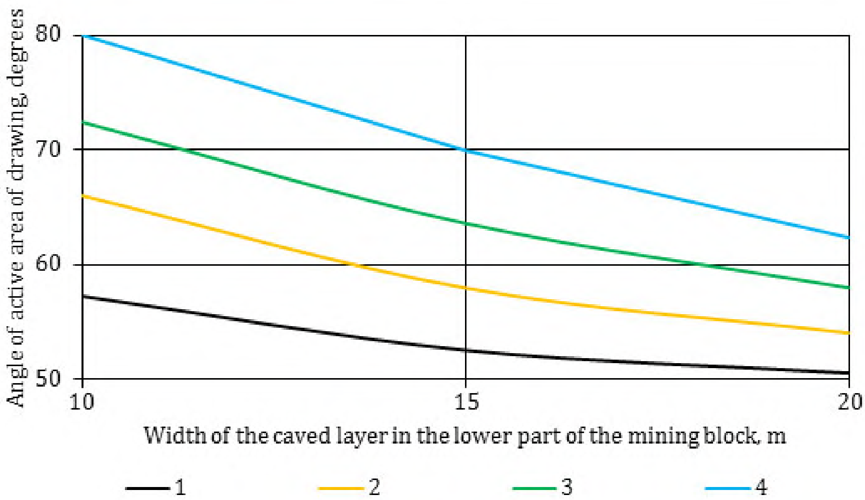


Figure 6. Dependency of the angle of ore drawing on the distance between a drawpoint and the inclined surface at the ore deposit dip of 45 degrees and the width of the caved layer in the lower part of the mining block of the "triangle" of the footwall: 1, 2, 3 and 4 – the width of the caved layer, 4, 6, 8 and 10 m respectively.

Let us consider how the angle of inclination of the enclosing plane and the angle of caved ore drawing impact the draw crater radius. The calculation scheme is given in figure 7.

Considering the right triangle ABC and knowing the width of the ore layer under breaking, the angle of inclination of the enclosing plane, the radius of the draw crater R_r (triangle BCD) is determined by the formula

$$R_r = h_{el} \times \tan\gamma = d \times \tan\beta_{r.r} \times \tan(90 - \beta_{r.r}), \quad (11)$$

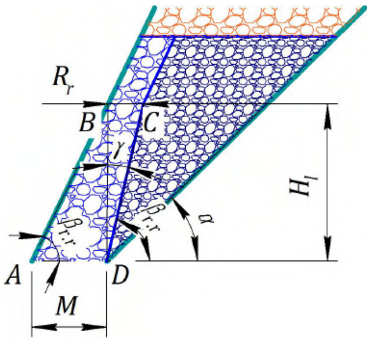


Figure 7. Scheme for determining the radius of the draw crater depending on the angle of the inclined plane.

where γ is the angle of internal friction, degrees; $\beta_{r.r}$ is the angle of inclination of the enclosing plane, degrees; d is the width of the base of the ore layer under breaking, m.

Thus, according to the known values from the theory of drawing caved ore under the country rocks, the radius of the draw crater is determined. The results of the calculations are given in table 4.

Table 4. Change in the radius of the drawing crater depending on the angle of the enclosing plane inclination.

Angle of the enclosing plane inclination, degrees	Radius of the drawing crater depending on the first loosening factor, m				
	1.1	1.2	1.3	1.4	1.5
45	4.4	4.1	3.3	2.5	2.0
50	4.8	4.5	3.7	2.9	2.4
55	5.3	5.0	4.2	3.4	2.9
60	6.0	5.6	4.8	4.0	3.5
65	7.0	6.5	5.6	4.9	4.4
70	8.2	7.7	6.8	6.1	5.5
75	10.0	9.7	8.9	8.2	7.5

According to the obtained values, the dependency of the drawing crater radius on the angle of the enclosing plane inclination can be built (figure 8).

As is seen in figure 8, an increase in the angle of plane inclination leads to the increase of the draw crater radius from 2.0 to 7.5 m at the first loosening factor of 1.5. A decrease in the first loosening factor from 1.5 to 1.1 results in the increase of the draw crater radius from 2.0-7.5 m to 4.4-10.0 m.

Thus, by changing the angle of plane inclination and increasing the width of the active drawing area, it is possible to reduce ore losses on the footwall.

Ore reserves remaining outside the active drawing area are determined by the expression, t

$$Q_l = (3 \times b + 0.5 \times h_{el} \times (\coth \alpha - \coth \beta_{r.r})) \times H \times L \times \gamma_o. \tag{12}$$

The volume of diluting rocks, when drawing caved ore, is determined by the formula, m^3

$$V_r = \frac{\pi \times h_l \times b^2}{3} \times \left(2 - \frac{3 \times (l_d - h_l \times k_l)}{b} + \frac{3 \times (l_d - h_l \times k_l)}{b}\right), \tag{13}$$

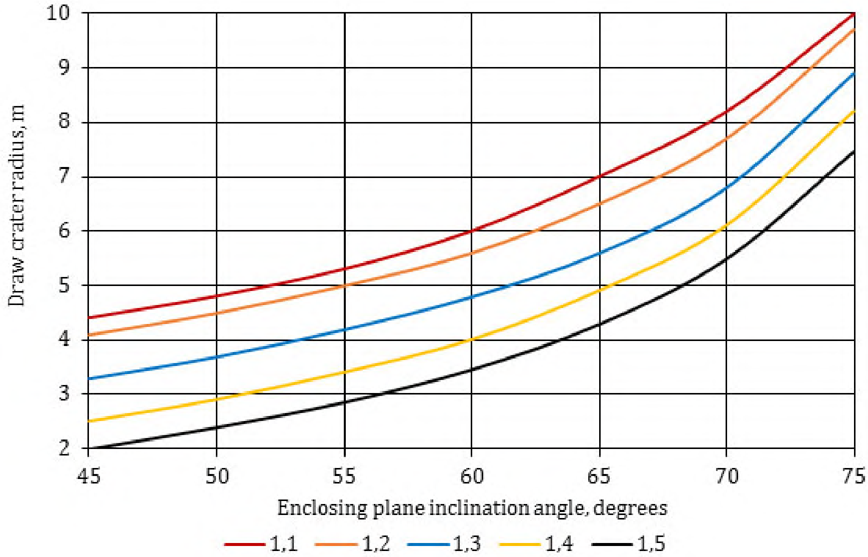


Figure 8. Dependencies of the change in the radius of the draw crater on the angle of the plane inclinatione.

where l_d is the distance between the drawpoint and the inclined plane, m.

Caved ore losses during its drawing under the overcompacted layer are determined by the expression, %

$$V = \frac{k_r \times Q_r + \left(L \times M - \frac{\pi \times N}{12} \times \left(d_{cr}^2 + d_{cr} \times d + d^2\right)\right) \times \frac{d_{cr} - d}{2} \times \gamma_{r.o} \times \tan \beta_{r.r}}{Q}, \quad (14)$$

where k_r is the ratio of ore extraction from the overcompacted layer, unit fr.; Q_r is the ore reserve in the overcompacted layer, t; N is the number of drawpoints; $\gamma_{r.o}$ is the volumetric weight of loosened ore, t/m^3; d_{cr} is the diameter of the draw crater, m.

Depending on physical and mechanical properties of the caved ore, ridges remaining on the block sill depend on the angle of ore drawing. At Kryvyi Rih iron ore basin, the angle of ore drawing does not exceed 68 degrees.

Analytical calculations of losses and dilution of ore during deposit mining using an overcompacted layer for the ore deposit dip of 60 degrees and an angle of the inclined plane of 70 degrees are given in table 5.

Based on the results of the analytical calculations performed, dependencies of changes in losses and dilution of ore during its drawing under the overcompacted layer are built figure 9.

As is seen in figure 9, an increase in the thickness of the overcompacted layer of ore decreases ore losses from 15 to 8%, and dilution increases from 6 to 16%. This is due to the fact that a decrease in the thickness of the overcompacted layer decreases the semi-minor axis of the ellipsoid of drawing, and the radius of the drawing flow under the inclined plane decreases accordingly. To minimize ore losses and dilution, it is advisable to locate the drawpoint in the block sill at a distance that provides formation of the 20 to 25 m high ellipsoid of drawing.

Thus, when applying the sublevel forced caving system using an overcompacted ore layer, it is possible to significantly reduce ore losses and dilution to enhance extraction of ore mass without additional costs. With the 22 m thick overcompacted layer, ore losses and dilution can be reduced from the actual 14 and 16% to 10 and 9% respectively.

Table 5. Ore losses and dilution during deposit mining using the overcompacted layer under the inclined plane.

Thickness of the overcompacted layer, m	Ore clogging, tons	Ore losses, tons
5	2088	5987
10	1605	4427
15	1337	3067
20	966	1256
25	854	1103
30	635	966

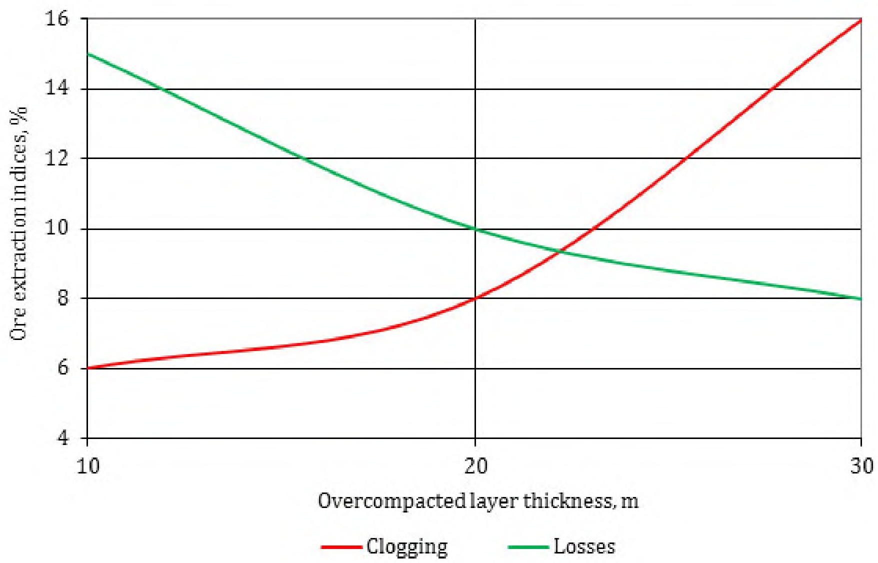


Figure 9. Dependencies of changes in losses and dilution of ore during its drawing under the over-compacted layer and the inclined plane located at the angle of 70 degrees and with the ore deposit dip of 60 degrees.

6. Conclusions

The results of the analysis of methods for determining parameters of figures of caved ore drawing from stoping blocks enable the conclusion that there is no single methodology. Each of the methods has its own conditions of application. However, parameters of the figure of drawing are significantly impacted by the degree of crushing, the material mobility ratio, the shape and condition of the surface, the compaction factor, the mode of drawing.

The results of the studies performed enable proving that the width of the active drawing area is impacted by not only rock pressure, but also the ore deposit dip angle and the enclosing surface represented by the hanging wall or created by gradual ore breaking. Thus, losses of ore on the footwall can be reduced by changing the angle of inclination of the plane and increasing the width of the active drawing area.

It is established for the first time that an increase in the thickness of the overcompacted ore layer leads to increases in the semi-minor axis of the ellipsoid of drawing and the width of the active area, which results in decreased losses and dilution of ore during its drawing from the stoping block. It is established that in order to minimize ore losses and dilution when using level mining systems, the drawpoint should be located in the block sill at a distance that provides formation of the 20 to 25 m high ellipsoid of drawing.

Using an overcompacted ore layer can significantly reduce ore losses and dilution and enhance extraction of ore mass without additional costs. Thus, the 22 m thick overcompacted layer enables ore losses and dilution reduction from the actual 14 and 16% to 10 and 9% respectively.

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References
[1] Stupnik N, Kalinichenko V, Pismennij S and Kalinichenko E 2015 Features of underlying levels opening at "ArsellorMittal Kryvyi Rih" underground mine *New Developments in Mining Engineering 2015: Theoretical and Practical Solutions of Mineral Resources Mining* ed Pivnyak G, Bondarenko V and Kovalevska I (London: CRC Press) pp 39–44 URL https://doi.org/10.1201/b19901-8
[2] Stupnik M, Kalinichenko O, Kalinichenko V, Pysmennyi S and Morhun O 2018 *Mining of Mineral Deposits* **12**(4) 56–62 URL https://doi.org/10.15407/mining12.04.056
[3] Morkun V, Morkun N and Tron V 2015 *Metallurgical and Mining Industry* **7**(8) 18–21 URL http://ds.knu.edu.ua/jspui/handle/123456789/2262
[4] Fedko M B, Muzyka I O, Pysmennyi S V and Kalinichenko O V 2019 *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu* **1** 37–41 URL https://doi.org/10.29202/nvngu/2019-1/20
[5] Khomenko O, Kononenko M, Kovalenko I and Astafiev D 2018 *E3S Web Of Conferences* **60**(6) 00009 URL https://doi.org/10.1051/e3sconf/20186000009
[6] Petlovanyi M, Lozynskyi V, Zubko S, Saik P and Sai K 2019 *Rudarsko Geolosko Naftni Zbornik* **34**(1) 83–91 URL https://doi.org/10.17794/rgn.2019.1.8
[7] Kononenko M and Khomenko O 2010 Technology of support of workings near to extraction chambers *New Techniques and Technologies in Mining - Proceedings of the School of Underground Mining* (London: CRC Press) pp 193–197 URL https://www.researchgate.net/publication/322961259_
[8] Pysmenniy S, Shvager N, Shepel O, Kovbyk K and O D 2020 *E3S Web of Conferences* **166** 02006 URL https://doi.org/10.1051/e3sconf/202016602006
[9] Morkun V, Morkun N and Tron V 2015 *Metallurgical and Mining Industry* **7**(7) 16–19 URL https://www.metaljournal.com.ua/assets/Journal/english-edition/MMI_2015_7/003Vladimir%20Morkun%2016-19.pdf
[10] Golik V, Komashchenko V, Morkun V and Gaponenko I 2015 *Metallurgical and Mining Industry* **7**(7) 383–387 URL https://www.metaljournal.com.ua/assets/Journal/english-edition/MMI_2015_7/061Vladimir%20Golik%20383-----387.pdf
[11] Khomenko O, Tsendjav L, Kononenko M and Janchiv B 2017 *Mining Of Mineral Deposits* **11**(4) 86–95 URL https://doi.org/10.15407/mining11.04.086
[12] Khomenko O, Kononenko M and Netecha M 2016 *Mining of Mineral Deposits* **10**(1) 50–56 URL https://doi.org/10.15407/mining10.01.050
[13] Morkun V and Morkun N 2018 *Archives of Acoustic* **43**(1) 61–67 URL http://ds.knu.edu.ua/jspui/handle/123456789/2135
[14] Golik V I, Komashchenko V I, Morkun V S, Morkun N V and Hryshchenko S M 2018 *Science and Innovation* **14**(3) 29–39 URL http://doi.org/10.15407/scine14.03.029

[15] Khomenko O and Kononenko M 2019 *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu* **3** 12–21 URL https://doi.org/10.29202/nvngu/2019-3/3
[16] Stupnik N I, Fedko M B, Kolosov V A and Pismennyy S V 2014 *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu* **5** 21–25 URL http://ds.knu.edu.ua/jspui/handle/123456789/3125
[17] Kosenko A V 2021 *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu* **1** 19–25 URL https://doi.org/10.33271/nvngu/2021-1/019
[18] Stupnik M, Kalinichenko V, Fedko M, Pysmennyi S, Kalinichenko O and Pochtarev A 2022 *Mining of Mineral Deposit* **16**(2) 33–41 URL https://doi.org/10.33271/mining16.02.033
[19] Pysmennyi S, Peremetchyk A, Chukharev S, Fedorenko S, Anastasov D and Tomiczek K 2022 *IOP Conference Series: Earth and Environmental Science* **1049**(1) 012029 URL https://doi.org/10.1088/1755-1315/1049/1/012029
[20] Krupnik L, Yelemessov K, Bortebayev S and Baskanbayeva D 2018 *Eastern-European Journal of Enterprise Technologies* **96**(12) 22–27 URL https://doi.org/10.15587/1729-4061.2018.151038
[21] Baskanbayeva D D, Krupnik L A, Yelemessov K K, Bortebayev S A and Igbayeva A E 2020 *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu* **5** 68–74 URL https://doi.org/10.33271/NVNGU/2020-5/068
[22] Stupnik N and Kalinichenko V 2012 *Geomechanical Processes during Underground Mining: School of Underground Mining 2012* (London: CRC Press) p 15–17
[23] Morkun V, Morkun N, Tron V, Serdiuk O and Dotsenko I 2019 *Archives of Acoustics* **44**(1) 161–167 URL https://doi.org/10.24425/aoa.2019.126362
[24] Tron V, Haponenko A, Haponenko I and Paranyuk D 2020 *E3S Web of Conferences* **201** 01025 URL https://doi.org/10.1051/e3sconf/202020101025
[25] Golik V, Morkun V, Morkun N and Gaponenko I 2018 *Mining of Mineral Deposits* **12**(3) 63–70 URL https://doi.org/10.15407/mining12.03.063
[26] Porkuian O, Morkun V, Morkun N and Serdyuk O 2019 *Acta Mechanica et Automatica* **13**(4) 262–270 URL http://ds.knu.edu.ua/jspui/handle/123456789/2089
[27] Stupnik N, Kalinichenko V, Fedko M and Mirchenko Y 2013 *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu* **1** 44–48
[28] Kalinichenko V, Dolgikh O and Dolgikh L 2019 *E3S Web of Conferences* **123** 01047 URL https://doi.org/10.1051/e3sconf/201912301047
[29] Stupnik M, Kalinichenko V, Fedko M and Kalinichenko O 2018 *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu* **6** 20–25 URL https://doi.org/10.29202/nvngu/20186/5
[30] Stupnik M, Kalinichenko V, Bah I, Pozdniakov V and Keita D 2014 *Progressive Technologies of Coal, Coalbed Methane, and Ores Mining* 159–162 URL https://doi.org/10.1201/b17547
[31] Agoshkov M I, Borisov S S and Boyarskiy V A (eds) 1983 *Razrabotka rudnykh i nerudnykh mestorozhdeniy* (Moskva: Nedra)
[32] Malakhov G M, Petrenko P D and Dvornikov V A 1973 *Izv. vuzov* **4** 9–13
[33] Korzh V A 1997 *Vidomosti Akademiyi hirnychykh nauk Ukrayiny* **2** 54–56
[34] Kononenko M, Khomenko O, Savchenko M and Kovalenko I 2019 *Mining Of Mineral Deposits* **13**(3) 22–30 URL https://doi.org/10.33271/mining13.03.022
[35] Khomenko O, Rudakov D and Kononenko M 2011 *Technical And Geoinformational Systems In Mining* 271–275 URL https://doi.org/10.1201/b11586-45
[36] Myronova I 2016 *Mining of Mineral Deposits* **10**(2) 64–71 URL https://doi.org/10.15407/mining10.02.064
[37] Bazaluk O, Petlovanyi M, Lozynskyi V, Zubko S, Sai K and Saik P 2021 *Sustainability* **13**(2) 834 URL https://doi.org/10.3390/su13020834
[38] Bazaluk O, Petlovanyi M, Zubko S, Lozynskyi V and Sai K 2021 *Minerals* **11**(8) 858 URL https://doi.org/10.3390/min11080858
[39] Lyashenko V, Andreev B and Dudar T 2022 *Mining of Mineral Deposits* **16**(1) 43–51 URL https://doi.org/10.33271/mining16.01.043
[40] Lozynskyi V, Medianyk V, Saik P, Rysbekov K and Demydov M 2020 *Rudarsko Geolosko Naftni Zbornik* **35**(2) 23–32 URL https://doi.org/10.17794/rgn.2020.2.3
[41] Takhanov D, Muratuly B, Rashid Z and Kydrashov A 2021 *Mining of Mineral Deposits* **15**(1) 50–58 URL https://doi.org/10.33271/mining15.01.050
[42] Panchenko V, Sobko B, Lotous V, Vinivitin D and Shabatura V 2021 *Mining of Mineral Deposits* **15**(1) 87–95 URL https://doi.org/10.33271/mining15.01.087
[43] Zeylik B, Arshamov Y, Baratov R and Bekbotayeva A 2021 *Mining of Mineral Deposits* **15**(2) 134–142 URL https://doi.org/10.33271/mining15.02.134
[44] Nurpeissova M, Rysbekov K, Levin E, Derbisov K and Nukarbekova Z 2021 *Engineering Journal of Satbayev University* **143**(5) 3–9 URL https://doi.org/10.51301/vest.su.2021.i5.01

[45] Kononenko M and Khomenko O 2021 *Mining of Mineral Deposits* **15**(2) 111–123 URL https://doi.org/10.33271/mining15.02.111
[46] Myronova I 2015 *New Developments in Mining Engineering 2015: Theoretical and Practical Solutions of Mineral Resources Mining* 193–197 URL https://doi.org/10.1201/b19901-35
[47] Rakishev B R, Auezova A M, Kuttybayev A Y and Kozhantov A U 2014 *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu* **6** 22–27 URL http://www.nvngu.in.ua/index.php/en/home/1008-engcat/archive/2014/contents-no-6-2014/geology/2854-specifications-of-the-rock-massifs-by-the-block-sizes
[48] Rysbekov K, Bitimbayev M, Akhmetkanov D, Yelemessov K, Barmenshinova M, Toktarov A and Baskanbayeva D 2022 *Mining of Mineral Deposits* **16**(2) 64–72 URL https://doi.org/10.33271/mining16.02.064
[49] Bazaluk O, Rysbekov K, Nurpeisova M, Lozynskyi V, Kyrgizbayeva G and Turumbetov T 2022 *Frontiers in Environmental Sciencey* **10** 852591 URL https://doi.org/10.3389/fenvs.2022.852591
[50] Issayeva L, Togizov K, Duczmal-Czernikiewicz A, Kurmangazhina M and Muratkhanov D 2022 *Mining of Mineral Deposits* **16**(2) 14–21 URL https://doi.org/10.33271/mining16.02.014
[51] Rylnikova M V and Mitishova N A 2021 *Engineering Journal of Satbayev University* **143**(4) 10–15 URL https://doi.org/10.51301/vest.su.2021.i4.02
[52] Imashev A, Suimbayeva A, Zhunusbekova G, Zeitinova S, Kuttybayev A and Mussin A 2022 *Mining of Mineral Deposits* **16**(3) 61–66 URL https://doi.org/10.33271/mining16.03.061
[53] Kovrov O, Babiy K, Rakishev B and Kuttybayev A 2016 *Mining of Mineral Deposits* **10**(2) 55–63 URL https://doi.org/10.15407/mining10.02.055
[54] Malakhov G M, Bezukh V R and Petrenko P D 1968 *Teoriya i praktika obrushennoy rudy* (Moskva: Nedra)
[55] Korzh V A 1997 *Vidomosti Akademiyi hirnychykh nauk Ukrayiny* **3** 61–62
[56] Malanchuk Y, Moshynskyi V, Khrystyuk A, Malanchuk Z, Korniienko V and Abdiev A 2022 *Mining of Mineral Deposits* **16**(1) 68–76 URL https://doi.org/10.33271/mining16.01.068
[57] Peregudov V, Hryhoriev I, Joukov S and Hryhoriev Y 2020 *E3S Web of Conferences* **166** 02004 URL https://doi.org/10.1051/e3sconf/202016602004
[58] Joukov S, Lutsenko S, Hryhoriev Y, Martyniuk M and Peregudov V 2020 *E3S Web of Conferences* **166** 02005 URL https://doi.org/10.1051/e3sconf/202016602005
[59] Azarian V, Lutsenko S, Zhukov S, Skachkov A, Zaiarskyi R and Titov D 2020 *Mining of Mineral Deposits* **14**(1) 1–10 URL https://doi.org/10.33271/mining14.01.001
[60] Stupnik M and Kalinichenko V 2013 Magnetite quartzite mining is the future of Kryvyi Rig iron ore basin *Annual Scientific-Technical Colletion - Mining of Mineral Deposits* ed Pivnyak G, Bondarenko V, Kovalevs'ka I and Illiashov M (London: CRC Press) pp 49–52 URL https://doi.org/10.1201/b16354-10
[61] Stupnik M, Kalinichenko V, Bah I, Pozdniakov V and Keita D 2014 *Progressive Technologies of Coal, Coalbed Methane, and Ores Mining* ed Bondarenko V, Kovalevs'ka I and Ganushevych K (London: CRC Press) p 159–162 URL https://doi.org/10.1201/b17547
[62] Korzh V A 1999 *Razrabotka rudnykh mestorozhdeniy* **69** 81–93
[63] Mironova I and Borysovs'ka O A 2014 *Progressive Technologies of Coal, Coalbed Methane, and Ores Mining* **69** 333–340 URL https://doi.org/10.1201/b17547-57
[64] Korzh V A 1999 *Vidomosti Akademiyi hirnychykh nauk Ukrayiny* **1** 36–39
[65] Petlovanyi M, Ruskykh V, Zubko S and Medianyk V 2020 *E3S Web of Conferences* **201** 01027 URL https://doi.org/10.1051/e3sconf/202020101027
[66] Petlovanyi M V, Zubko S A, Popovych V V and S S K 2020 *Voprosy Khimii i Khimicheskoi Technologii* **6** 142–150 URL https://doi.org/10.32434/0321-4095-2020-133-6-142-150
[67] Blizniukov V H and Lutsenko S O 2017 *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu* (1) 44–49 URL http://nbuv.gov.ua/UJRN/Nvngu_2017_1_9
[68] Lutsenko S A 2017 *Quality – Access to Success* **18**(S1) 226–230 URL https://www.proquest.com/openview/87ac497268d7644e316b4c1bfc24d289/1.pdf?pq-origsite=gscholar&cbl=1046413
[69] Gargul K, Boryczko B, Bukowska A, Hołda A, Małecki S and Tora B 2021 *Archiv.Civ.Mech.Eng* **21**(1) 1–13 URL https://doi.org/10.1007/s43452-021-00184-9
[70] Suponik T, Franke D, Nuckowski P, Matusiak P, Kowol D and Tora B 2021 *Minerals* **11**(3) 1–21 URL https://doi.org/10.3390/min11030281
[71] Korzh V A 1997 *Vidomosti Akademiyi hirnychykh nauk Ukrayiny* **3** 103–105
[72] Bolatova A, Kuttybayev A, Kainazarov A, Hryhoriev Y and Lutsenko S 2022 *Series of geology and technical sciences* **1** 33–38 URL https://doi.org/10.32014/2022.2518-170X.137
[73] Petlovanyi M and Mamaikin O 2019 *ARPN Journal of Engineering and Applied Sciences* **14**(20) 3492–3503 URL https://ir.nmu.org.ua/handle/123456789/154573
[74] Morkun V V, Fischerauer G, Morkun N, Tron V and Haponenko A 2022 Determining rock varieties on the

basis of fuzzy clustering of ultrasonic measurement results *Proceedings of the 3rd International Workshop on Intelligent Information Technologies & Systems of Information Security, Khmelnytskyi, Ukraine, March 23-25, 2022* (*CEUR Workshop Proceedings* vol 3156) ed Hovorushchenko T, Savenko O, Popov P T and Lysenko S (CEUR-WS.org) pp 274–283 URL `https://ceur-ws.org/Vol-3156/paper20.pdf`

[75] Golik V, Komashchenko V, Morkun V and Zaalishvili V 2015 *Metallurgical and Mining Industry* **7**(4) 325–329 URL `https://www.metaljournal.com.ua/assets/MMI_2014_6/MMI_2015_4/047-GolikKomashchenkoMorkunZaalishvili.pdf`

[76] Pysmennyi S, Fedko M, Chukharev S, Rysbekov K, Kyelgyenbai K and Anastasov D 2022 *IOP Conference Series: Earth and Environmental Science* **970**(1) 012040 URL `https://doi.org/10.1088/1755-1315/970/1/012040`

[77] Moshynskyi V S, Korniienko V Y, Malanchuk Y Z, Khrystyuk A O, Lozynskyi V H and Cabana E C 2021 *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu* **6** 35–41 URL `https://doi.org/10.33271/nvngu/2021-6/035`

[78] Yelemessov K, Nauryzbayeva D, Bortebayev S, Baskanbayeva D and Chubenko V 2021 *E3S Web of Conferences* **280**(1) 07007 URL `https://doi.org/10.1051/e3sconf/202128007007`

[79] Kalinichenko O, Fedko M, Kushnerov I and Hryshchenko M V 2019 *E3S Web of Conferences* **123** 01015 URL `https://doi.org/10.1051/e3sconf/201912301015`

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Identification of resistance torque on the roller cone bit in the drill rod rotation drive

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Identification of resistance torque on the roller cone bit in the drill rod rotation drive

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Abstract. There is a problem of increasing the durability of the roller cone bit of the drilling rigs used in the quarries of Ukraine. One of the effective ways to solve it is to apply the control method of maintaining a constant flow of mechanical power in the bottom hole zone. The implementation of such a control method leads to the necessity of controlling and limiting the resistance torque on the roller cone bit. To solve the problem of determining the resistance torque, we used methods of parameter identification: the Luenberger observation device with adaptation to external influences; estimation of the resistance torque using an extended observation object; the theory of regulators adapting to perturbations. It has been established that the most rational method of identifying the resistance torque on a roller cone bit is an astatic monitoring device, which allows to implement a method of controlling the rotation of the drill rod by a drive mechanism that maintains a constant flow of mechanical energy through the roller cone bit and increases the durability of the roller cone bit.

1. Introduction

The operation of the drilling rig is characterized by the transformation of the flow of electromagnetic energy coming from the power supply system into a flow of mechanical energy, which is released in the form of non-productive losses and turned into useful work, going to the destruction of rock and transportation of drilling fines onto the wellhead [1]. Energy flows are formed and directed through the following channels: axial force – power of linear movement of the drilling rod; rotation frequency – rock destruction power; compressed air pressure and flow rate – drilling fines evacuation (cuttings) power. Each channel has an individual type of energy converter; these are: adjustable electro-hydro-mechanical drive of drill bit supplying; adjustable electromechanical drive of roller cone bit rotation; nonadjustable electromechanical drive of compressor to remove drilling fines from the surface of the hole bottom.

Figure 1 shows a diagram of the formation and transformation of the electromagnetic energy flow of the power supply system into the mechanical energy flow on a roller cone.

There is a problem of improving the working capacity of a roller cone bit, since it wears most of all, since its cutting structure and supports work in an abrasive environment. During operation, the bit absorbs high static and dynamic loads, and is also subjected to intensive destruction from material fatigue and abrasive wear. The flow of rotational energy is directed not only to the destruction of the rock, but also to the destruction of the bit itself.

In order to increase the performance of a roller cone bit by maintaining the power flow in the bottom hole zone, the method of drilling process control [2] with control of the drives for the feeding and rotating mechanisms has been developed, where hard mechanical characteristics

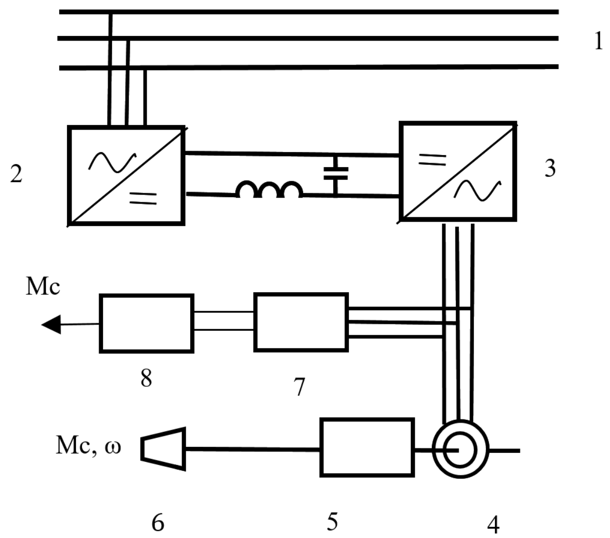

Figure 1. Diagram of the formation, transformation and control of the flow of mechanical energy on the cone bit by the rotation drive of the drilling rig rod. Designate: 1 – power supply network; 2 – rectifier; 3 – inverter; 4 – asynchronous motor; 5 – reducer; 6 – cone bit; 7 – coordinate converter of the ABC axes to the d-q system; 8 – identifier of the resistance torque on the cone bit.

are formed on the roller cone bit when penetrating soft formations and soft mechanical characteristics – in stronger formations.

When drilling rocks with intermittent physical and mechanical properties, the control method provides automatic selection of mechanical characteristics depending on the strength characteristics of the rock.

Implementation of the developed method of drilling process control leads to the necessity of measuring, controlling and limiting on permissible levels of resistance torque on the roller cone bit.

2. Related work

The need to modernize the park of drilling rigs for blasting wells used in quarries in Ukraine is an actual task, since they have exhausted their physical reserves, being in operation for 1.5 – 2 normative time limits.

Machine-building and electro-technical plants of Ukraine have modern technologies, on the basis of which they are capable of serial production of new generation drilling rigs on their own. Since 2003 the Novokramatorsk Machine-Building Plant has been working on the development of a new generation drill rig SBShS-250H with AC drive systems.

The essential question when developing the control system of the drilling rig rotation drive is the choice of its control method. There are known methods of control, realizing the support at a constant level of one of the parameters: bit rotation frequency, resistance torque on the bit [3], linear speed of bit movement, axial pressure on the bit, consumed power of rotation drive.

There are kinematic and energy criteria of the working capacity of a roller cone bit. The kinematic criterion monitors bit speed or linear penetration rate per bit, which is an indirect evidence of bit cutting structure wear.

Energy criterion of the working capacity of a roller cone bit is proposed in [2]. In this case, it is necessary to control the resistance torque on the bit and its rotation frequency. The time integral of their product is the energy released by the bit armament on the bottom hole. By stabilizing the energy release rate at a constant level, it is possible to get the maximum bit durability, since the cutting structure material is under a constant load. This can be achieved by keeping the power of destruction of the rock at a constant level with varying strength of the drilled rocks. The power delivered will depend on the resistance torque on the bit and the rotational speed of the bit. If the rotational speed is easy to measure, then measuring the resistance torque on the bit is in principle impossible due to the aggressive environment in the bottom hole area. Measuring power by voltage and current of the drive system will lead to errors due to their nonlinear dependence and dynamic torque presents.

Based on the energy criterion of bit durability, we choose the most rational way of controlling the rotation drive of the roller cone drill bit, which controls the power released in the bottom hole zone of the roller cone bit. With this approach, it is necessary to determine the resistance torque on the bit, using one of the methods of identifying the external influences based on the state observer [4, 5].

3. Results

The system of differential equations describing the dynamics of an induction motor in the d-q coordinate system, tied to the vector of the main flux linkage, has the form [5]:

$$\frac{d\psi_r}{dt} = -\frac{R_r}{L_r}\psi_r + k_r R_r I_d; \frac{dI_d}{dt} = \frac{R_s + k_r^2 R_r}{L_s'} I_d + \frac{k_r R_r}{L_s' L_r}\psi_r + \omega_{\psi r} I_d + \frac{1}{L_s'} U_d;$$

$$\frac{dI_q}{dt} = -\frac{R_s + k_r R_r}{L_s'} I_d - \omega_{\psi r} I_d - \frac{k_r}{L_s'} p_n \psi_r \omega + \frac{1}{L_s'} U_d; \frac{d\omega}{dt} = \frac{k_m \psi_r I_q - M_c}{J},$$

where ψ_r, L_r, R_r – the rotor flux linkage, inductance and active resistance; I_d, I_q – transverse and longitudinal components of the motor stator current; R_s, L_s' – stator resistance and inductance; ω, $\omega_{\psi r}, p_n$ – angular frequency of rotation of the rotor, flux linkage of the rotor and the number of pole pairs of the stator winding; U_d, U_q – transverse and longitudinal components of the stator voltage; M_m – mutual induction between the stator and the rotor (inductance of the magnetization circuit); denoted: $k_r = M_m/L_r, k_s = M_m/L_s, L_s' = \sigma L_s, \sigma = 1 - k_s Kr, k_m = 3p_n k_r/2$; σ – leakage coefficient; J is the dynamic moment inertia of the drive mechanical link.

The coordinate system is oriented in the direction of the vector of the main flux linkage, which makes it possible to separately control the flux linkage of the rotor and the transverse component of the stator current. This makes it possible to synthesize a system with normalized dynamic parameters, which controls the flux coupling and the longitudinal stator current on one channel, and the rotor speed and the transverse component of the stator current on the other channel (vector control system for induction squirrel-cage motor).

Equations describing dynamic processes in the control channel by the active (torque-forming) component of induction motor stator current [6]

$$\begin{cases} \frac{dI_q}{dt} = -\frac{R_s + k_r R_r}{L_s'} I_d - \omega_{\psi r} I_d - \frac{k_r}{L_s'} p_n \psi_r \omega + \frac{1}{L_s'} U_d; \\ \frac{d\omega}{dt} = \frac{k_m \psi_r I_q - M_c}{J}. \end{cases} \tag{1}$$

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There are four disturbing signals in the control object: rotor flux linkage – ψ_r; resistance torque – M_c; cross-coupling – $\omega_{\psi r}I_d$; electromotive force of rotation frequency – $k_r\psi_r p_n\omega/L'_s$.

We believe that the rotor flux linkage is maintained at a constant level through the control channel of the reactive (flux-forming) current of the motor stator. Compensation of the cross-coupling and the electromotive force of the rotation frequency is carried out by introducing additional links, zeroing out the perturbing actions from the indicated influences. Compensation of the cross-coupling is achieved by decoupling of the control channels. The direct compensation uses signals proportional to the product of the instantaneous frequency rotation of the rotor flux linkage vector $\omega_{\psi r}$ and the reactive component of the stator current, as well as the product of the rotor frequency rotation and the current value of the rotor flux linkage. Therefore, these perturbations on the control object are not taken into account when identifying the torque of resistance [7, 8].

After these simplifications one can forming the state vector

$$X = \begin{pmatrix} x_1 \\ x \end{pmatrix} = \begin{pmatrix} I_d \\ \omega \end{pmatrix}$$

and denoting $k_m = 3p_nk_r/2$ it is convenient to represent the object under consideration by a system of linear differential equations written in matrix form:

$$\begin{cases} \dot{X} = AX + Bu + W; \\ Y = CX, \end{cases} \tag{3}$$

where the matrix coefficients are defined

$$A = \begin{pmatrix} -\ (R_s + k_rR_r)/L'_s & -k_rp_n\psi_r/L'_s \\ k_m\psi_r/J & 0 \end{pmatrix}, B = \begin{pmatrix} 1/L'_s \\ 0 \end{pmatrix}, W = \begin{pmatrix} 0 \\ M_c/J \end{pmatrix}, C = (1\ 0).$$

Let us study the problem of determining the resistance torque on the bit M_c, using various methods of identifying the external influences that cannot be directly measured. The methods under consideration apply the so-called observer, i.e., its mathematical model working in parallel with the object. The main attention is paid to the stability of the system, which is ensured by a proper choice of its natural frequencies (modes) on the complex plane.

The extended object method assumes [9] that the change in the external action is subject to some differential equations, which together with the equations of the main object define the extended system. In this case perturbing influences become state variables of the extended object.

In our case, taking into account that the rate of transient processes in the object exceeds the rate of change M_c, we obtain $M_c \approx const$.

The original system of equations presented in vector-matrix form

$$\begin{cases} \dot{X} = AX + Bu + W; \\ Y = CX; \\ \dot{W} = 0, \end{cases}$$

transform to a form convenient for further analysis:

$$\begin{cases} \dot{X}^{*} = A^{*}X^{*} + B^{*}u + W; \\ Y^{*} = C^{*}X^{*}, \end{cases} \tag{4}$$

where the notation for matrix coefficients is accepted

$$A^{*} = \begin{pmatrix} -\ (R_s + k_r R_r)/L'_s & -k_r p_n \psi_r / L'_s & 0 \\ k_m \psi_r / J & 0 & -1/J \\ 0 & 0 & 0 \end{pmatrix},$$

$$B^{*} = \begin{pmatrix} 1/L'_s \\ 0 \\ 0 \end{pmatrix}, X^{*} = \begin{pmatrix} x_1 \\ x_2 \\ x_3 \end{pmatrix} = \begin{pmatrix} I_s 2 \\ \omega \\ M_c \end{pmatrix}, C^{*} = (1\ 0\ 0).$$

We construct the observing device in the form of a mathematical model, which is described by the equation

$$\dot{\hat{X}} = A^{*}X + B^{*}u + W + L(Y - C^{*}\ \hat{X}), \tag{5}$$

where L – some unknown matrix of size $n \times 1$; n is system order.

The last term in (4), taking into account the difference between the outputs of the object and the model, corrects the observer so that the condition is fulfilled $\hat{X}\ (t) - X^{*}(t) \to 0$ when $t \to \infty$. Such an observer is called an asymptotic identifier.

If we denote $\widetilde{X} = \hat{X} - X^{*}$, then from (3) and (4) we obtain equations for the estimation error:

$$\dot{\widetilde{X}} = A^{*}\widetilde{X} + L(Y - C^{*}\widetilde{X}) \text{ or } \dot{\widetilde{X}} = (A^{*}\widetilde{X} - LC^{*})\widetilde{X}.$$

In accordance with the scientific statements put forward in [10,11], which establish the relation between the total observability and the characteristic polynomial of a matrix $A^{*} - LC^{*}$ with an arbitrary desired set of roots, we check for the system (3) the observability condition, which consists in that the rank of the observation matrix

$$Q_n = (C^T \vdots A^{*T} C^T \vdots\ (A^{*T})^2 C^T \vdots \ldots \vdots\ (A^{*T})^{n-1} C^T)$$

must match the order of the system n.

For the system under study, we obtain:

$$Q_n = (C^T \vdots A^{*T} C^T \vdots\ (A^{*T})^2 C^T) = \begin{pmatrix} 1 & -(R_s + k_r R_r)/L'_s & ((R_s + k_r R_r)/L'_s)^2 - k_r k_m p_n \psi_r^2 / J L'_s \\ 0 & -k_r p_n \psi_r / L'_s & k_r p_n \psi_r (R_s + k_r R_r)/(L'_s)^2 \\ 0 & 0 & k_r p_n \psi_r / L'_s J \end{pmatrix}.$$

The matrix rank Q_n is 3, that is, it coincides with the order of the system. In this case, the condition of complete observability is satisfied.

The characteristic polynomial for the matrix $A^{*} - LC^{*}$, (where $det[\lambda I - A^{*} + LC^{*}]$, where I is the identity matrix) is determined by the expression:

$$\det \begin{pmatrix} \lambda + (R_s + k_r R_r)/L'_s + l_1 & k_r p_n \psi_r / L'_s & 0 \\ -k_m \psi_r / J + l_2 & \lambda & 1/J \\ l_3 & 0 & \lambda \end{pmatrix} =$$

$$= \lambda^3 + (\frac{R_s + k_r R_r}{L'_s} + l_1)\lambda^2 + \frac{k_r p_n \psi_r}{L'_s}(\frac{k_m \psi_r}{J} - l_2)\lambda + \frac{k_r p_n \psi_r}{J L'_s} l_3 \quad (6)$$

We select the elements of the matrix $L = (l_1\ l_2\ l_3)^T$ in such a way that the polynomial turns into the Newton binomial

$$(\lambda + \beta)^3 = \lambda^3 + 3\lambda\beta^2 + 3\lambda^2\beta + \beta^3; (\beta > 0).$$

Whence, by equating the coefficients at the same degrees of the polynomial, we obtain

$$\begin{cases} (R_s + k_r R_r)/L'_s + l_1 = 3\beta; \\ (k_r p_n \psi_r / L'_s)(k_m \psi_r / J - l_2) = 3\beta^2; \\ k_r p_n \psi_r l_3 / J L'_s = \beta^3. \end{cases} \quad (7)$$

To solve system (6), it is necessary to choose the value determines the position of the matrix eigenvalues $A^* - LC^*$ on the complex plane and, consequently, the rate of convergence $\hat{X}(t)$ to $X^*(t)$.

Usually, values β are used in 2...3 times greater than the maximum of the numbers $|Re\lambda_0|$, where λ_0 is the eigenvalues of the object's matrix. Let's find them by solving the equation

$$\det |Re\lambda_0 I - A| = 0$$

$$\begin{vmatrix} \lambda_0 + (R_s + k_r R_r)/L'_s & k_r p_n \psi_r / L'_s \\ -k_m \psi_r / J & \lambda_0 \end{vmatrix} = \lambda_0^2 + \lambda_0 (R_s + k_r R_r)/L'_s + k_m k_r p_n \psi_r^2 / J L'_s = 0$$

$$\lambda_0(1,2) = -(R_s + k_r R_r)/2L'_s \pm \sqrt{(R_s + k_r R_r)/2L'_s)^2 - k_m k_r p_n \psi_r^2 / J L'_s}.$$

We choose $\beta = \gamma (R_s + k_r R_r)/2L'_s$, where the value γ within 2. . . 3 is accepted.

Then, in accordance with the obtained equations of system (6), we find the values of the correction coefficients:

$$\begin{cases} l_1 = \frac{3\gamma}{2}\frac{R_s + k_r R_r}{L'_s} - \frac{R_s + k_r R_r}{L'_s} = \frac{R_s + k_r R_r}{L'_s}(\frac{3\gamma}{2} - 1); \\ l_2 = \frac{k_m \psi_r}{j} - \frac{3}{4}\gamma^2 \frac{(R_s + k_r R_r)^2}{k_r p_n \psi_r L'_s}; \\ l_3 = \frac{1}{8}\gamma^3 \frac{J(R_s + k_r R_r)^3}{k_r p_n \psi_r (L'_s)^2}. \end{cases} \quad (8)$$

Consequently, the structural diagram and the values of the correction coefficients are generally defined for the observing device (4).

It is known that the method of transition to an extended object requires complete observability of this object [5]. An astatic observing device [11] is free from this restriction [12], the construction of which we will consider for the problem to be solved when the vector of disturbing influences contains one nonzero element.

For system (2) in this case it is possible to construct an observing device described by equations:

$$\dot{\widetilde{X}} = A\widetilde{X} + Bu + L(Y - C\widetilde{X}) + K\int_0^t (Y - C\widetilde{X})dt, \quad (9)$$

where $L = (l_1\ l_2)^T$ and $K = (0\ k)^T$ are matrices with yet unknown coefficients.

From (8) and the structure of the matrix, we see that the integral term is added only to the equation of system (8) that corresponds to the equation of system (2) containing a nonzero perturbation.

The equation for the estimation error $\widetilde{X}(t) = \hat{X}(t) - X(t)$ takes the form:

$$\dot{\widetilde{X}} = (A - LC)\widetilde{X} - kC\int_0^t \widetilde{X}(t)dt - W. \tag{10}$$

It follows from the last relation that the condition $\hat{X}(t) \to X(t)$ or $\widetilde{X} \to 0$ when $t \to \infty$ (and actually for the damping time of the natural component of the transient) is satisfied if

$$-kC\int_0^t (\hat{X}(t) - X(t))dt = W.$$

Thus, the observer (8) allows us to identify the perturbation W. The choice of matrices L and K makes it possible to control the rate of this process.

When applied to the object under consideration (2), the described technique leads to the following result. Let us differentiate equation (9), assuming that the perturbation the perturbation does not change over the transition time:

$$\dot{\widetilde{X}} = (A - LC)\widetilde{X} - kCX.. \tag{11}$$

Let's write the system (10) in the expanded form:

$$\begin{cases} \ddot{\widetilde{x}}_1 = (a_{11} - l_1)\,\dot{\widetilde{x}}_1 + a_{12}x_2; \\ \ddot{\widetilde{x}}_2 = (a_{21} - l_2)\,\dot{\widetilde{x}}_1 - k\widetilde{x}_1, \end{cases} \tag{12}$$

where a_{ij} is matrix A element.

Using the method of excluding the unknowns, we transform the system (11) into a third-order differential equation:

$$\dddot{\widetilde{x}}_1 - (a_{11} - l_1)\,\ddot{\widetilde{x}}_1 - a_{12}(a_{21} - l_2)\,\dot{\widetilde{x}}_1 - a_{12}k\widetilde{x}_1 = 0,$$

whose characteristic polynomial has the form (taking into account values of a_{11}, a_{12}, a_{21})

$$\lambda^3 + (\frac{R_s + k_r R_r}{L'_s} - l_1)\lambda^2 + \frac{k_r p_n \psi_r}{L'_s}(\frac{k_m \psi_r}{j} - l_1)\lambda + \frac{k_r p_n \psi_r}{L'_s}k = 0. \tag{13}$$

$$\lambda^3 + (\frac{R_s + k_r R_r}{L'_s} - l_1)\lambda^2 + \frac{k_r p_n \psi_r}{L'_s}(\frac{k_m \psi_r}{j} - l_1)\lambda + \frac{k_r p_n \psi_r}{L'_s}k = 0. \tag{14}$$

The polynomial (12) coincides completely with the characteristic polynomial (5). This allows one, if a binomial arrangement of the roots $(\alpha + \beta)^3$ is desired, to write down, using the solution obtained earlier (7):

$$\begin{cases} l_1 = \frac{R_s + k_r R_r}{L'_s}(\frac{3\gamma}{2} - 1); \\ l_2 = \frac{k_m \psi_r}{j} - \frac{3}{4}\gamma^2 \frac{(R_s + k_r R_r)^2}{k_r p_n \psi_r L'_s}; \\ l_3 = \frac{1}{8}\gamma^3 \frac{J(R_s + k_r R_r)^3}{k_r p_n \psi_r (L'_s)^2}. \end{cases}$$

where γ has the same meaning as in (7).

Equations (8) written element by element in expanded form:

$$\begin{cases} \dot{\hat{x}}_1 = a_{11}\,\hat{x}_1 + a_{12}\,\hat{x}_2 + l_1(x_1 - \hat{x}_1) + \frac{1}{L'_s}u_q; \\ \dot{\hat{x}}_2 = a_{21}\,\hat{x}_1 + l_2(x_1 - \hat{x}_1) + k\int_0^t (x_1 - \hat{x}_1)dt, \end{cases}$$

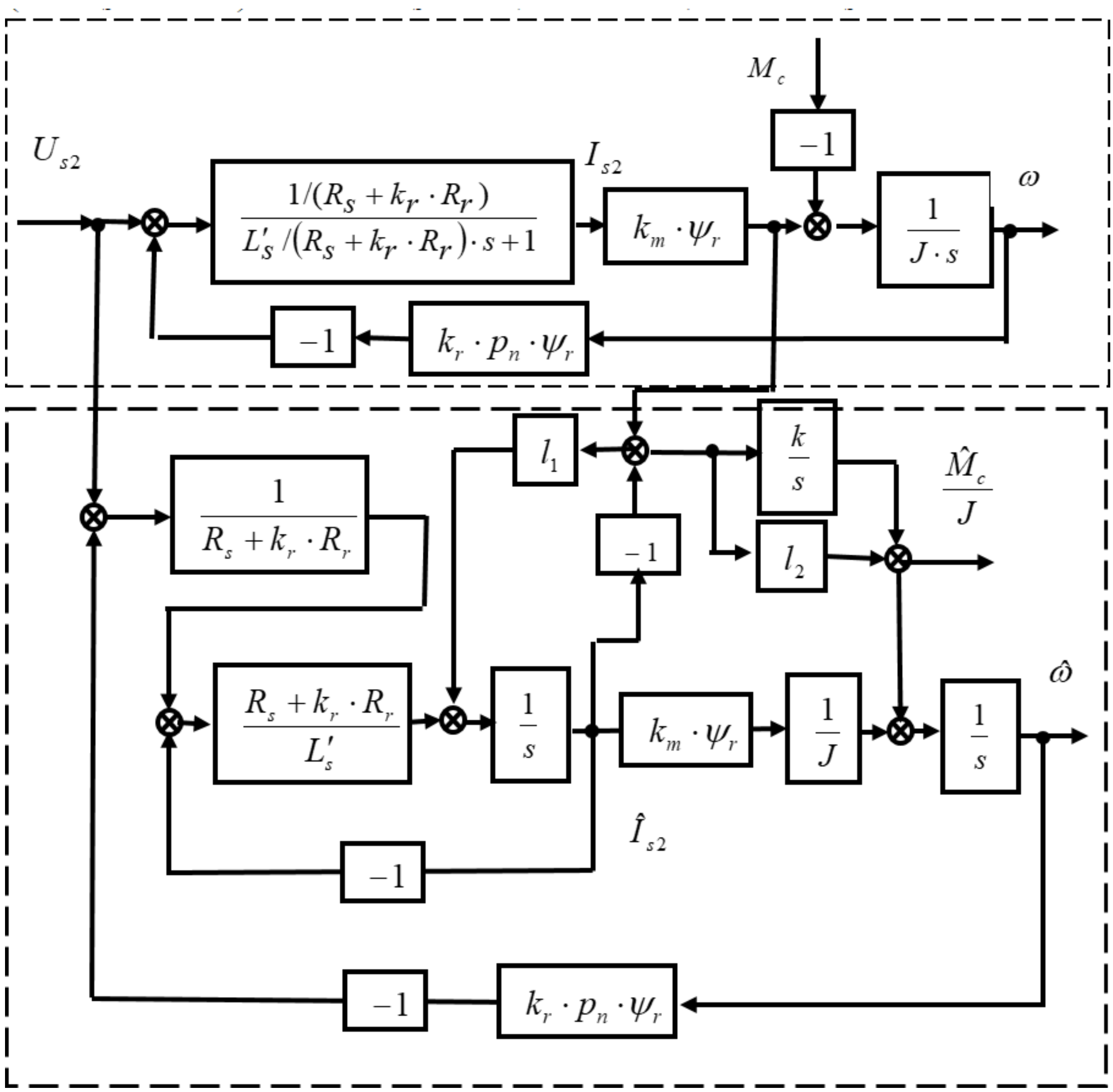

Figure 2. Structural diagram of the observing device.

explicitly define the block diagram of the observing device shown in figure 2.

Analysis of the efficiency of the method for identifying the resistance torque on a roller bit was carried out on the basis of simulation in the environment of the mathematical extension package Simulink of the MATLAB system, where realized mathematical model of the drilling rod rotation electromechanical system.

The mathematical model takes into account the change of instantaneous values of output voltage of semiconductor converter with pulse-width modulation, full system of equations of asynchronous motor of the drilling rod. Discreteness of digital control system is 2 μs, voltage inverter frequency is 2000 Hz.

Parameters of setting of the observer are calculated according to the initial data of the electrical equipment of the drilling rod SBShS250N head rotation drive. The drilling rig is equipped with AT-04 transistor drive with squirrel cage induction motor AMRU280M4BU2,

Table 1. Initial parameters of the identification object.

$R_s + k_r R_r$	L'_s	k_r	k_m	p_n	ψ_r	J	M
ohm	mH	p.u.	p.u.	p.u.	wb	kg m^2	kg m
0.152	2.73	0.977	0.842	2.0	1.502	1.2	580

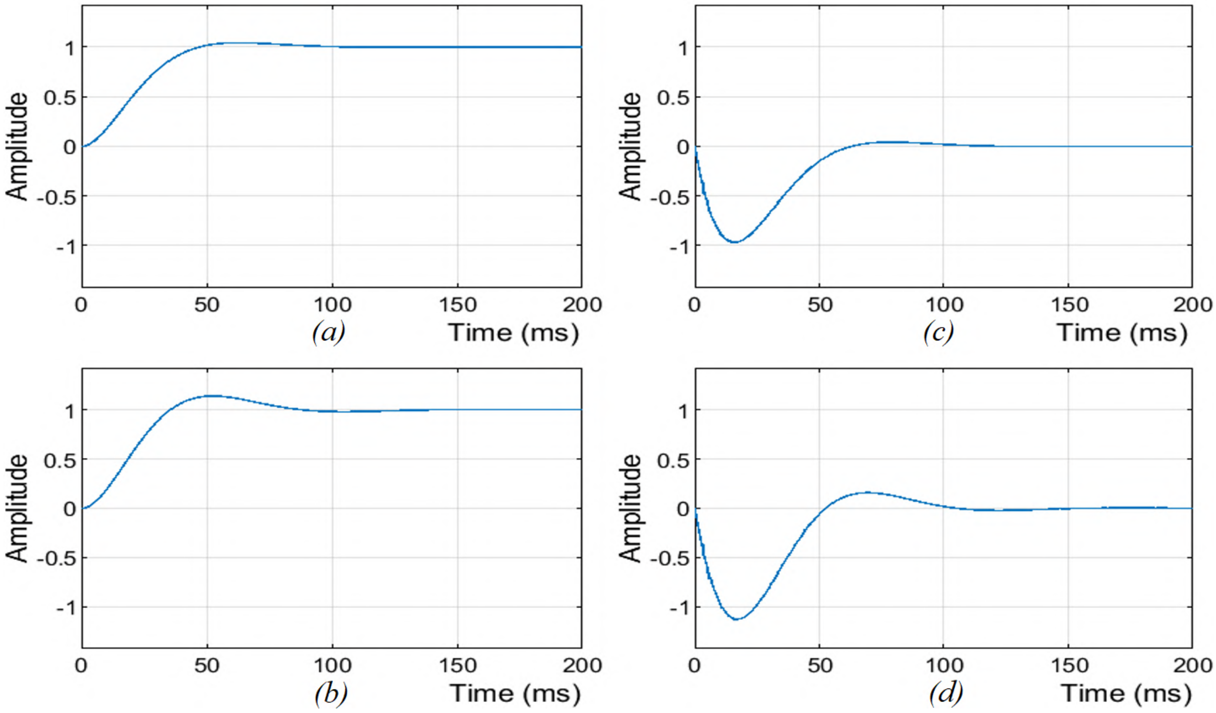

Figure 3. Graphs of the resistance torque (a, b) and the determination error (c, d) during their identification on a roller bit, given in p.u.

1480 rpm, 90 kW. Technical data are given in the table 1.

Calculated plots of resistance torque identification on the roller cone bit using the astatic observer and the binomial root distribution ($\beta = 55.6$; figure 3(a)) and the Butterworth distribution (($\beta = 83.4$; figure 3(b)), are shown in figure 3.

Figure 3 shows the calculated graphs of the error in finding the resistance torque by an astatic observer with a binomial distribution of roots ($\beta = 55.6$; figure 3(c)) and the Butterworth distribution ($\beta = 83.4$; figure 3(d)), In all graphs, the torque amplitudes are shown in relative units (p.u.). Torques are reduced to the rated motor torque $M = 580$ kg m.

4. Conclusions

1. The disturbing influence from the load in the system of electric drive can be effectively restored by the observer, to which the signals of the supply voltage and current of motor. Beside it is necessary to introduce three corrective links: two of which have proportional and one has integral dynamic characteristics. At the output of the observer, a signal that is proportional to the ratio of the resistance torque on the working body of the drive system to the moment of inertia is explicitly allocated.

2. Identification of the resistance torque on the roller cone bit allows to realize the way of controlling the drive of the drill rod rotation when the mechanical energy constant flow on the roller cone bit is maintained by forming "hard" mechanical characteristics in the drive of the rotation when drilling in soft and broken formations and "soft" mechanical characteristics when drilling in hard undisturbed formations that will increase the life of the bit.

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References

[1] Pankov V A 2005 *Mining journal* (2) 92–94
[2] Khilov V S 2003 Drilling control method Patent UA 61548
[3] Khilov V, Tryputen M, Kuznetsov V, Babyak M, Maksim K and Gorodny O 2020 Effect of The Types of Drive Systems of Drilling Rigs on The Rock Breaking Dynamics *2020 IEEE 7th International Conference on Energy Smart Systems (ESS)* pp 315–319 URL `https://doi.org/10.1109/ESS50319.2020.9160265`
[4] Kozhevnykov A A, Khilov V S, Borysevych O A and Belchitskyi O P 2012 *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu* **6** 86 – 91
[5] Tolochko O I 2004 *Analysis and synthesis of electromechanical systems with a state monitor* (Donetsk: Nord-press)
[6] Novotny D V and Lipo T A 1996 *Vector Control and Dynamics of AC Drives* Monographs in Electrical and Electronic Engineering (New York: Clarendon Press)
[7] Boldea I S and Nasar S A 2006 *Electric Drives* (New York: CRC Press, Taylor & Francis Group)
[8] Quang N P and Dittrich J A 2015 *Vector Control of Three-Phase AC Machines: System Development in the Practice* Power Systems (Berlin, Heidelberg: Springer) URL `https://doi.org/10.1007/978-3-662-46915-6`
[9] Luenberger D 1971 *IEEE Transactions on Automatic Control* **16**(6) 596–602 URL `https://doi.org/10.1109/TAC.1971.1099826`
[10] Hostetter G and Meditch J 1973 *IEEE Transactions on Automatic Control* **18**(3) 307–308 URL `https://doi.org10.1109/TAC.1973.1100296`
[11] Andreev Y N 1976 *Control of finite-dimensional linear objects* (Moscow: Nauka)
[12] Kuzovkov N T 1976 *Modal control and monitoring devices* (Moscow: Mashinostroenie)

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Geometrization of Kryvbas iron ore deposits

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Abstract. Mining and geometrical prediction of iron ore deposit quality indices to solve problems of long-term and current planning intended to provide the most efficient performance of mining enterprises in terms of ore blending quality and increase rationalization of deposit development is an important aspect of geometrization. Investigations carried out to develop a mining-geometrical method for predicting indices of iron ore deposit quality are topical nowadays. The present study aims to enhance the methodology for geometrization of iron ore deposit quality indices for developing a mining-geometrical method of their prediction to provide rational mining. The research methodology consists in mining and geometrical modeling of quality indices and properties of the deposit, thus enabling determination of a certain relationship between components of a mineral, and, thereby, identification of the nature of these components' location in the mineral. The latter is essential in design, construction and operation of a mineral deposit. The obtained results allow predicting quality indices of the deposit, assessing mineral reserves and consequently planning and optimizing performance of mining enterprises. The developed methods enable increased efficiency of mining iron ore deposits of Kryvbas.

1. Introduction

Ukraine ranks third in the world as to calculated iron ore reserves which make over 62 Bn t. Most of these reserves (over 32 Bn t) are concentrated in Kryvyi Rih iron ore basin [1–5] and mined by open pit and underground methods. Distribution of iron ore reserves by enterprises of the Kryvyi Rih Basin is given in table 1. According to the US Geological Survey, during the past 15 years, Ukraine ranks sixth in terms of the amount of the ore mass mined (70-86 M t/y) [6–10].

To maintain a high level of annual ore production, mining enterprises are continuously enhancing technological processes.

Thus, in open pit mining, special attention is paid to drilling and blasting (enhancement of explosives and initiation methods) and technological operations (application of imported equipment during loading and transportation of the broken ore mass).

Underground mining systems are constantly being enhanced as well. To ensure appropriate quality of the extracted ore mass, enterprises widely apply open stoping systems. Imported self-propelled delivery equipment used in mining at considerable depths (over 1250 m) helps provide annual productivity of 2-3 M t [11–14].

Table 1. Distribution of iron ore reserves by enterprises of the Kryvyi Rih Basin

Mining enterprise	Reserves, Bn.t
JSC KRYVBASZALIZRUDKOM	6.120
JSC ArcelorMittal Kryvyi Rih	4.655
PJSC Northern mining and processing plant	3.480
PJSC Central Mining and Processing Plant	3.365
PJSC Southern mining and processing plant	2.650
PJSC Sukha Balka	1.950
PJSC Ingulets mining and processing plant	0.830
Together	23.05
The name of the ore deposit area:	
Tarapakovskoe deposit	1.350
Inter-mine site No 1	1.075
Inter-mine site No 2	1.450
Inter-mine site No 3	2.300
Inter-mine site No 4	1.475
Inter-mine site No 5	1.500
Together	9.15
Total	32.2

It should be noted that in working out Kryvyi Rih iron ore deposit, mining enterprises fail to increase annual ore production due to the fact that when designing or enhancing the technology, they use the data of mining and geometrical assessment of the deposit obtained in the previous century.

Planning mining production processes and performance of a mining enterprise is an important task even at the stage of deposit opening [15–19]. It can be ensured by application of mining and geometrical methods. At this, an important role is played by mining, geological and geometrical parameters and the nature of the deposit position which can be determined by methods of subsoil geometry [20–23].

A very important task that can be solved by geometrization methods is to determine stability of a rock massif under the stress-strain state. This enables determining measures to maintain rock massif stability [24–27].

A significant task of subsoil geometrization consists in increasing efficiency of drilling and blasting as an important factor for mining enterprise performance [28–32]. This task, in turn, is associated with that of monitoring the state of the rock massif [33–37] and closely related to methods of mining processes control [38–42].

Another important task involves selective mining based on assessment of geological, geochemical and geomechanical fields [43–47]. Methods of geometrization provide assessment and rational processing of man-made mineral formations [48–52].

Planning operation of a mining enterprise on the basis of mining and geometrical methods results in high economic indicators [53–57] ensured by rationalizing and optimizing mining operations.

Mining and geometrical assessment of the deposit is the most expedient when based on methods of analyzing geological data, among which geostatistical methods are the most effective [58–62]. This problem is closely related to the task of assessing and predicting the quality of reserves applying self-organization methods [63–65].

2. Purpose

The purpose of the study is geometrization of the iron ore deposit. A particularly important aspect of geometrization of iron ore mineral deposits involves mining and geometrical prediction of their quality indices to solve problems of long-term and current planning intended to provide the most efficient performance of mining enterprises in terms of ore blending and increase rationalization of deposit development.

The most promising methods for assessing indicators of the deposit include geometrization ones based on the use of a set of self-organizing methods and geostatistical methods of assessment [66, 67] which are developed and enhanced in the present work.

3. Methods

Processing the initial geological data requires a lot of sampling; the content of samples influences the quality in a certain block or area of the deposit. The problem of sampling is associated with application of various methods for determining weighted averages. The following two aspects of the problem are of great importance: the search procedure and a criterion for its completion. This criterion can be based on the value of the distance from the sample to the block or to the point where the composition is to be determined. In the most complex programs for calculating weighted averages, the search for points in an area is carried out on a plane or in a cone to ensure relative representativeness of all directions. This enables avoiding the effect of accumulation of samples in certain directions and their absence in others.

This step is, however, superfluous in case of kriging, since with accumulation of points, introduction of sample covariances allows considering automatically the influence of components of the cluster eliminating its excessive influence. Kriging helps to distribute weights among the nearest samples, if a constant density of sampling is not provided.

The grid density does not really influence the number of samples to be considered. Any kriging method does not indicate the number of samples required when assessing the ore composition in this block. From a theoretical standpoint, all available samples should be used. Nevertheless, it is clear that far-removed samples are of little interest. Therefore, it is obvious that the number of samples should not be too large. For example, considering sixteen points instead of twelve increases the calculation time by a factor of about 3, and sixteen samples instead of eight – by a factor of 8.

A sample removed from the block in a given direction for more than an influence interval (if any) is assumed to have a zero weight and should not be used. As an example, let us assess the exploration grid of Skelevatske deposit of ferruginous quartzites mined by the PivdGZK open pit. The deposit has for a long time been sampled in two ways. Detailed exploration is carried out by sampling the sludge of boreholes located irregularly with an interval of 50 to 200 meters. Operational exploration is carried out in the exploded mass by the point method. In case of homogeneous ores, pieces from an area of about a 50 m long (in the direction parallel to the bench slope) with a width determined by the size of the block to be exploded are selected in one sample. In case of heterogeneous ores, each type of quartzites is sampled separately. The sample weight is about 30 kg.

The data for assessment were selected along axis 77 along the strike towards the main direction of mining operations advance. The best method of assessment for actual conditions of Kryvbas iron ore deposits can be chosen by comparison. First, dependency of the natural component of variability on the sampling interval is assessed (figure 1-6), and then autocorrelation coefficients are determined at different sampling intervals (figure 7-12).

According to figures 1-6, at Skelevatske deposit, the minimum critical interval of geological exploration for both magnetite and total iron is 600 m. This enables the conclusion that

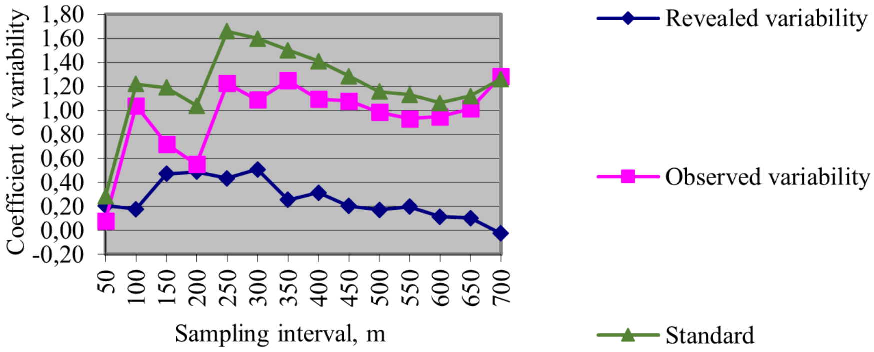

Figure 1. Dependency of the magnetite iron content variability on the sampling interval, hor. –165÷–180 m.

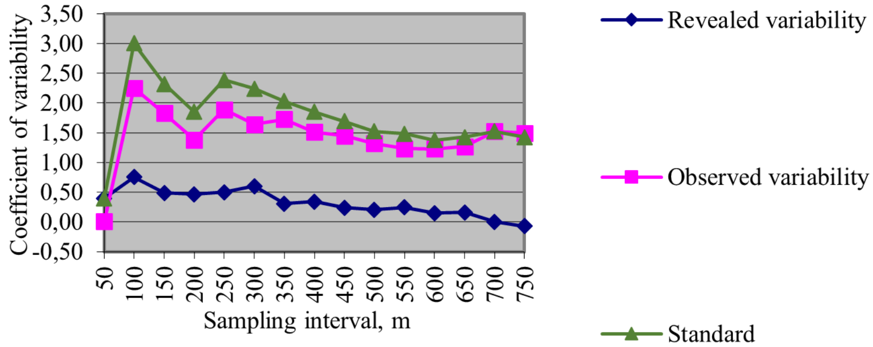

Figure 2. Dependency of the magnetite iron content variability on the sampling interval, hor. -180÷-195 m.

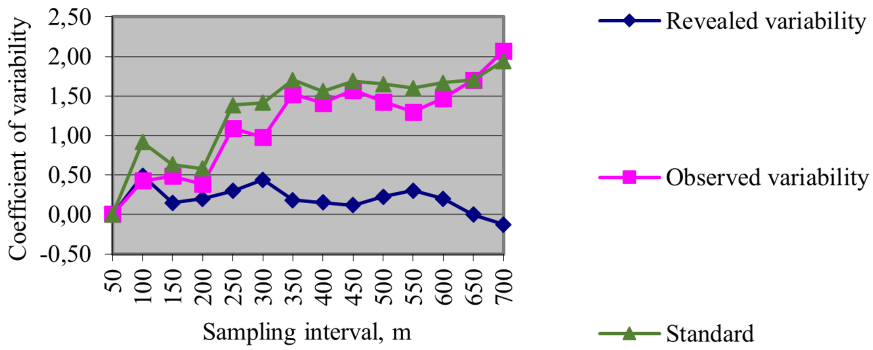

Figure 3. Dependency of the magnetite iron content variability on the sampling interval, hor. -195÷-210 m.

parameters of the exploration grid meet the requirements to them.

As is seen from figure 7-12, the autocorrelation coefficient provides ambiguous results. This is due to the fact that this coefficient inherently estimates, to this or that degree, deviation from the sample average value. Thus, in order to qualitatively assess a deposit with a nonlinear nature of index variability, the volume and interval of the sample should be selected with great accuracy and the initial data should be smoothed over as well, this being very time consuming and not always possible. In this very case, the graphs are sine curves with a growing amplitude.

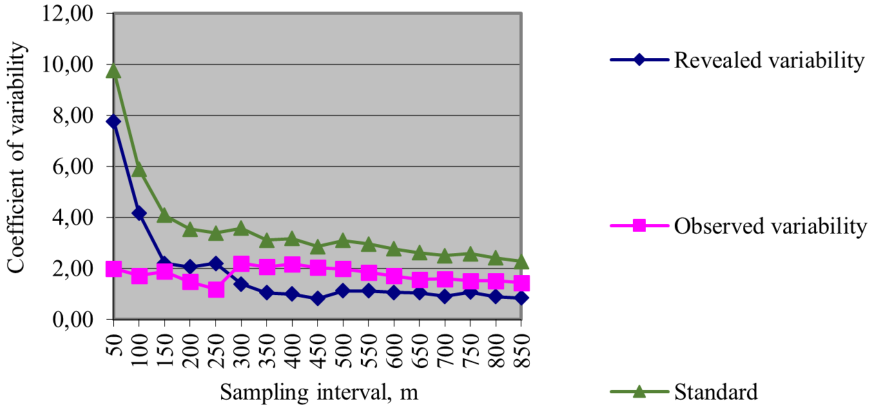

Figure 4. Dependency of the total iron content variability on the sampling interval, hor. -165÷-180 m.

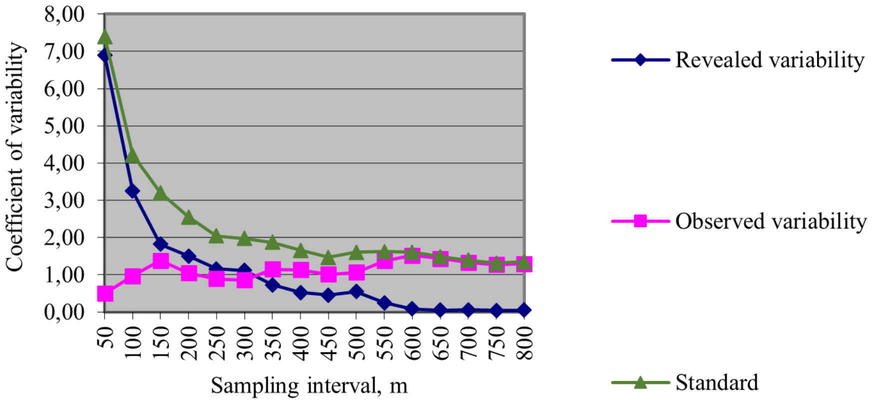

Figure 5. Dependency of the total iron content variability on the sampling interval, hor. -180÷-195 m.

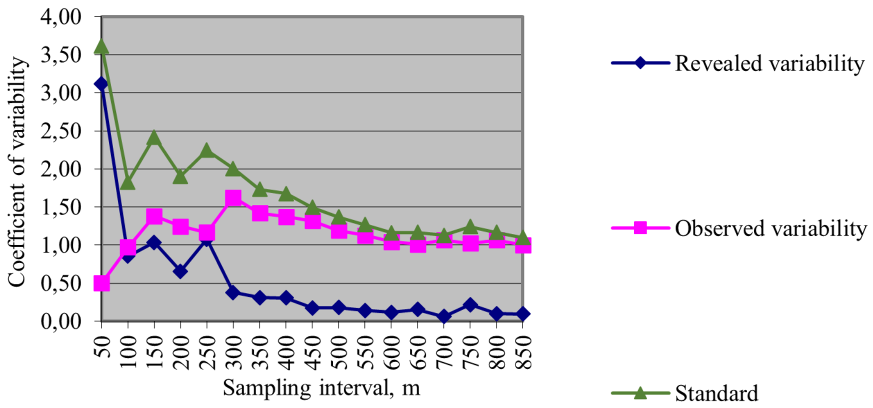

Figure 6. Dependency of the total iron content variability on the sampling interval, hor. -195÷-210 m.

Deviations of the indices of nearby points from the average also change in the close to sinusoidal manner, so the deposit can be said to actually have a sinusoidal component when obtaining the indices, and the autocorrelation coefficient is not quite relevant for assessing the exploration grid

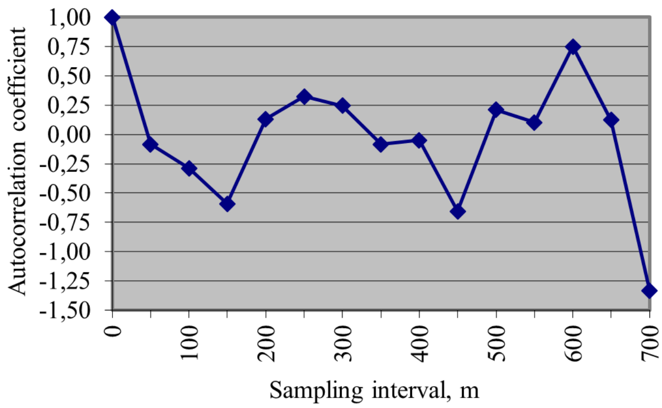

Figure 7. Dependency of the autocorrelation coefficient for the magnetite iron content on the sampling interval, hor. -165÷-180 m.

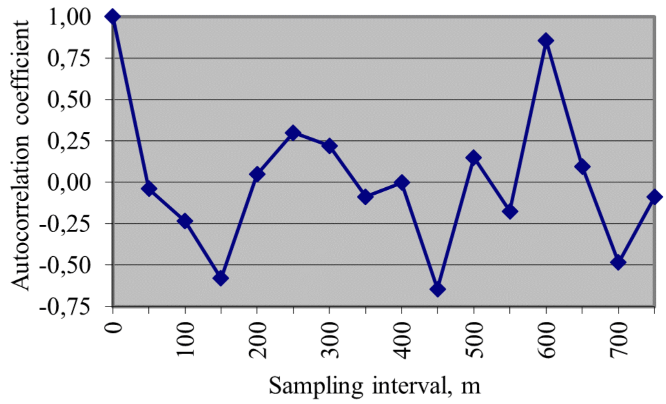

Figure 8. Dependency of the autocorrelation coefficient for the magnetite iron content on the sampling interval, hor. -180÷-195 m.

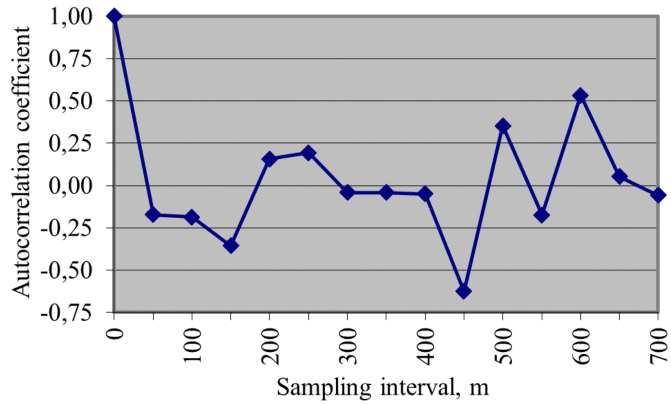

Figure 9. Dependency of the autocorrelation coefficient for the magnetite iron content on the sampling interval, hor. -195÷-210 m.

of Kryvbas iron ore deposits.

Determining the size of blocks under assessment can be set as a detailed assessment task,

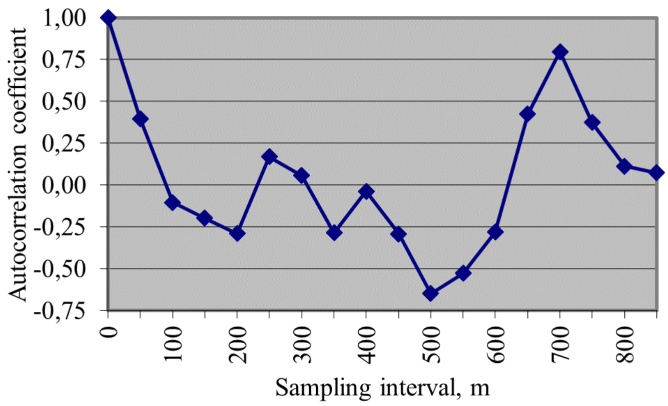

Figure 10. Dependency of the autocorrelation coefficient for the total iron content on the sampling interval, hor. -165÷-180 m.

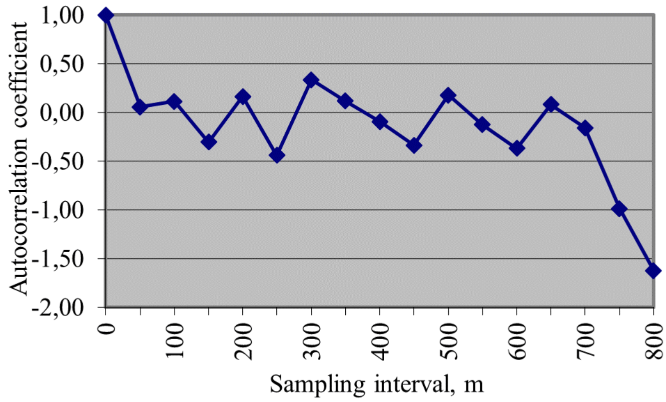

Figure 11. Dependency of the autocorrelation coefficient for the total iron content on the sampling interval, hor. -180÷-195 m.

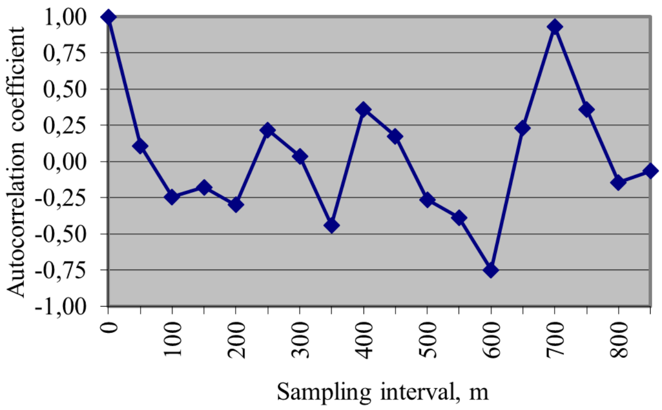

Figure 12. Dependency of the autocorrelation coefficient for the total iron content on the sampling interval, hor. -195÷-210 m.

distinguishing blocks of the smallest possible sizes. But this trend leads to an inexpedient cost of work and unreliable results. It turns out that small closely located blocks are characterized by very similar estimates. It should be kept in mind that as the block sizes decrease, estimation errors increase. Thus, a halving in linear dimensions of blocks leads to an 8-fold increase in the number of blocks to be assessed and, probably, the number of systems of linear equations to be solved. Accordingly, it can be assumed that the minimum block size should be at least a quarter of the average interval of the drilling grid. For example, blocks should have a side of 50 meters with a drilling grid pitch of 200 meters or a side of 200 meters at a pitch of 800 meters.

The most important geological and technological indices of ores of Skelevatske deposit of ferruginous quartzites include the content of magnetic iron which is associated with the total iron content. The nature of magnetic iron content in the exploded mass can be predicted based on the borehole sample data. At that, it is advisable to take the content of total and magnetic iron according to borehole sample data as arguments of prediction. Argument values in the inter-hole space can be determined through interpolation. It is advisable to use kriging as an interpolation method.

4. Results and discussion

The experiment was carried out at the PivdGZK open pit within axes 80-108 along and 89-109 across the strike at horizons -165÷-180 m, -180÷-195 m and -195÷-210 m. The area is located in the north-eastern part of the deposit, the area of oxidized ores makes its southern boundary. Structurally, the area is the eastern wing of the deposit synclinal. In the east, it is bounded by Tarapakiv fault, and its western border coincides with the deposit boundary.

The area is characterized by a sustained occurrence of rocks, weak development of folded deformations. Rocks dip to the north-north-east according to the general deposit sinking.

In the southern part of the area, i.e. on the boundary between the fourth ferruginous quartzites horizon and the fourth schistous horizon, there emerge a number of open folds the size and position of which are clearly seen on the map of the deposit as alternative outbreaks of schists (anticlinal) and quartzites (synclinal).

The initial geological data was obtained from horizon mining plans at a scale of 1:1000. Operational exploration was carried out to sample the exploded mass. At that, sampling areas were of irregular shape and different sizes. The dimensions of the areas ranged from 20 to 50 meters across. The content of total and magnetic iron by detailed exploration boreholes data and horizontal and vertical coordinates of the centers of the sampling areas were taken as arguments for prediction using the multidimensional heuristic prediction algorithm (MHPA). An irregular sampling grid was used for drilling detailed exploration boreholes. Distances between the boreholes ranged from 50 to 200 meters. With the help of kriging, isolines of the content of magnetic iron in the inter-hole space were built. In the center of each sampling area of the exploded mass, the value of magnetic iron was determined based on the available electronic model of isolines. All the acquired values were summarized in spreadsheets, which made the basis for building a predictive function according to the MHPA method. At that, at each stage of its building, credibility of the results obtained was proportional to the inverse distance between the center of the area of sampling the exploded mass and the nearest borehole of detailed exploration, as the greater this distance is, the greater the interpolation error becomes. Thus, the results of building a more accurate function had a greater priority in assessing the quality of the built predictive function.

The basic set of initial data enabled determining dependencies of the magnetic iron content in the exploded mass on that of magnetic iron determined by boreholes of detailed exploration and on the horizontal and vertical coordinates of the points. Three equations of predictive functions obtained by the MHPA method are presented in figures 13-15.

The found dependencies demonstrate that there is a dependency of the magnetic iron content in the exploded mass on that of the sampling data of detailed exploration boreholes, as of all the arguments involved in the MHPA procedure, significant numerical coefficients were determined

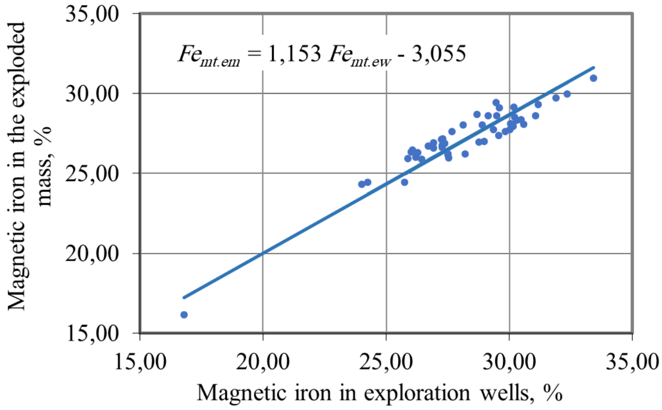

Figure 13. Relationship between the magnetic iron content according to the exploded rock mass sampling data and that of detailed exploration borehole data at hor. -165÷-180 m.

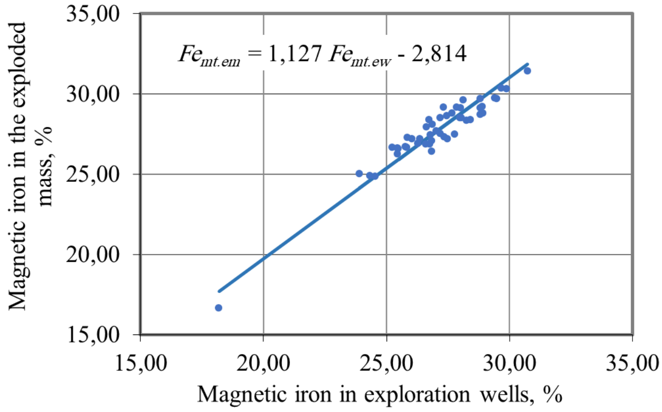

Figure 14. Relationship between the magnetic iron content according to the exploded rock mass sampling data and that of detailed exploration borehole data at hor. -180÷-195 m.

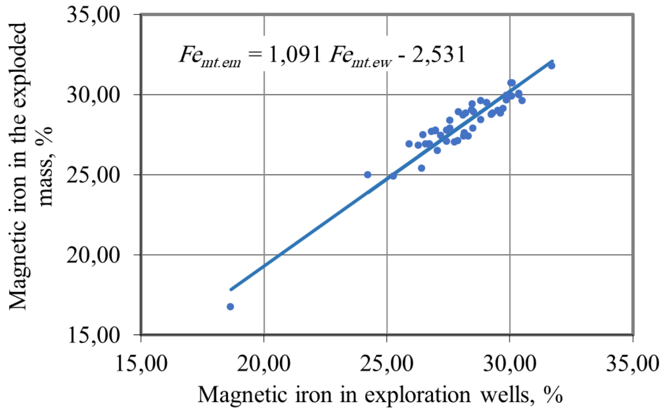

Figure 15. Relationship between the magnetic iron content according to the exploded rock mass sampling data and that of detailed exploration borehole data at hor. -195÷-210 m.

only for this value. During calculations, several types of ores with different properties were identified in the area under consideration and that resulted in determining different functional dependencies.

Areas with properties corresponding to these dependencies on a simulated set of data were obtained and grouped according to the MHPA procedure. At that, the iron content data obtained from detailed exploration boreholes were interpolated for 50 by 50 m square grid nodes.

Interpolation was performed using kriging. Predictive values of the content of magnetic iron associated with the content of magnetic iron in the exploded mass were determined in the square-grid nodes applying the MHPA procedure. Via kriging, these values were interpolated, which became the basis for long-term planning. Based on the interpolation, there were built plans of isolines of the predicted magnetite iron content which are presented in figures 16-18. Predicted data for current planning was received by adjusting the obtained electronic model according to operational exploration data at points spatial position of which was determined on the basis of production needs and was irregular.

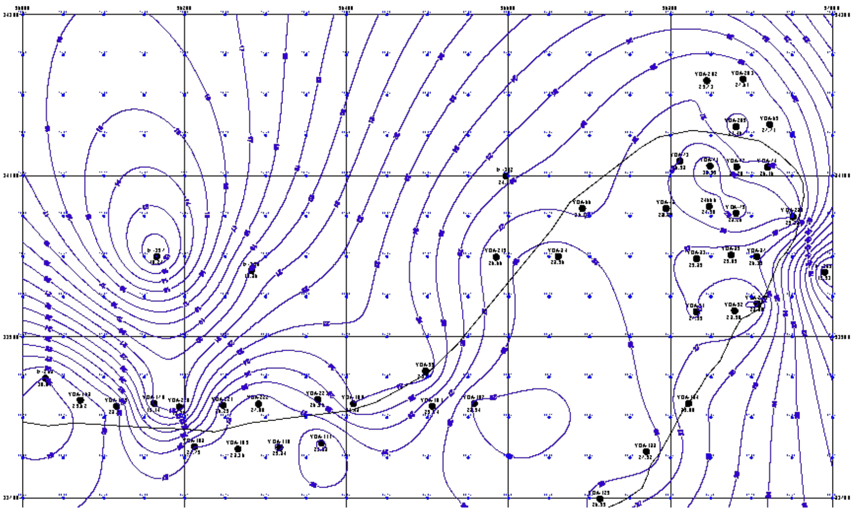

Figure 16. Plan of isolines of the predicted magnetic iron content at hor. -165÷-180 m.

5. Author contributions

The contributions of each author to this research are summarized as follows:

- As the author of the research concept, *Andrii Peremetchyk* played a pivotal role in developing the research methodology, collecting data, and setting the direction for the research. His contributions span across multiple sections of the article, including Introduction, Purpose, Methods, Results and discussion, and Conclusions.
- *Serhii Pysmennyi* actively participated in shaping the research methodology, conducting data analysis, and gaining a comprehensive understanding of the scientific essence of the research. His contributions are prominently featured in the Introduction, Purpose, Methods, and Results and discussion sections.
- *Serhii Chukharev* took charge of data analysis and was responsible for drafting the initial version of the article. His contributions are particularly evident in the Purpose, Methods, and Results and discussion sections.

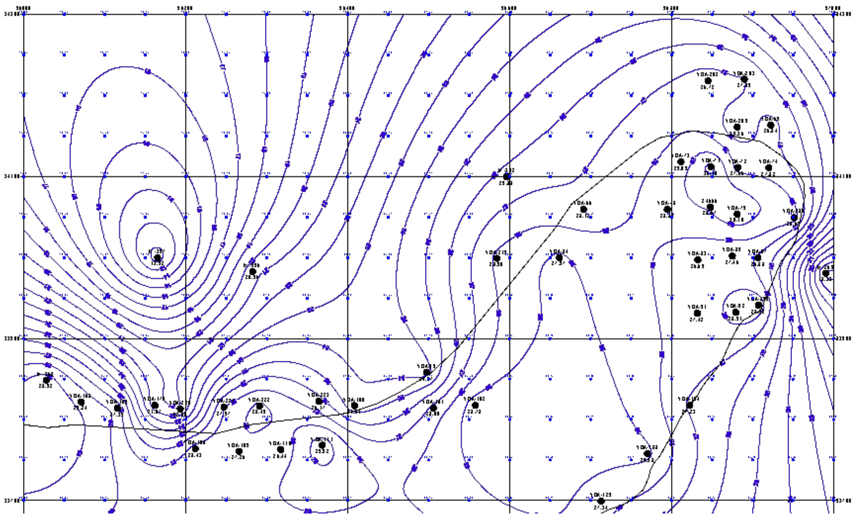

Figure 17. Plan of isolines of the predicted magnetic iron content at hor. -180÷-195 m.

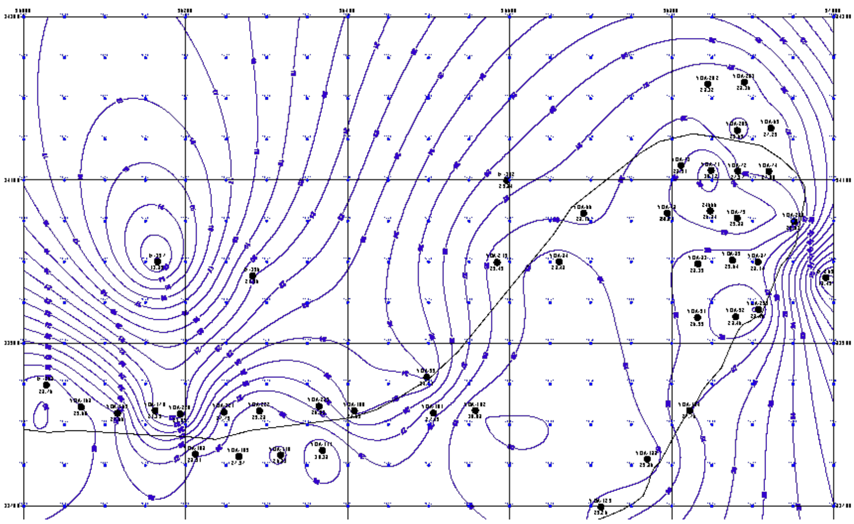

Figure 18. Plan of isolines of the predicted magnetic iron content at hor. -195÷-210 m.

- *Nataliia Shvaher* meticulously processed the raw data obtained during the study and conducted a thorough evaluation of the research results. Her significant contributions are concentrated in the Methods and Results and discussion sections.
- *Serhii Fedorenko* conducted a rigorous statistical assessment of the data's reliability and accuracy of the results obtained. His invaluable contributions are prominent in the Methods and Results and discussion sections.
- *Roland Iosif Moraru* held the responsibility for the overall design of the research methodology, ensuring its coherence and effectiveness. His primary contribution is in the Methods section.

Each author's specific role and expertise greatly enriched the research across various stages, ultimately leading to the comprehensive findings and conclusions presented in this article.

6. Conclusions

As a result of the study, an effective geometrization technique has been developed that meets the requirements of mining production. It enables assessment of mineral reserves and significantly increases efficiency of planning mining operations. The use of geostatistical methods makes it possible to assess and process the initial geological data. The developed self-organizing prediction algorithm is flexible in application, efficient, and can be used in various mining and geological conditions for geometrization of the deposit in order to provide planning and assessment of various mining technologies.

The relative error of the predicted value of the magnetic iron content in the exploded mass according to the developed method for long-term planning does not exceed 6.8%.

The positive results of prediction at the area under consideration are the basis for using the developed methods in other areas of the PivdGZK open pit.

Proceeding from the results, methods of geometrization of mineral deposits based on self-organization and geostatistical assessment are a very promising direction for further research. The considered methods require further development and enhancement in order to increase their efficiency and application at deposits of Kryvbas as well as other regions that produce both ore and non-metallic minerals.

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References

[1] Moshynskyi V, Malanchuk Z, Tsymbaliuk V, Malanchuk L, Zhomyruk R and Vasylchuk O 2020 *Mining of Mineral Deposits* **14**(2) 95–102 URL https://doi.org/10.33271/mining14.02.095
[2] Malanchuk Y, Korniienko V, Moshynskyi V, V S, Khrystyuk A and Malanchuk Z 2019 *Mining of Mineral Deposits* **15**(1) 66–74 URL https://doi.org/10.33271/mining13.01.049
[3] Malanchuk Z, Korniienko V, Malanchuk Y, V S and O V 2018 *Mining of Mineral Deposits* **12**(2) 76–84 URL https://doi.org/10.15407/mining12.02.076
[4] Morkun V, Morkun N and Tron V 2015 *Metallurgical and Mining Industry* **7**(8) 18–21 URL http://ds.knu.edu.ua/jspui/handle/123456789/2262
[5] Fedko M B, Muzyka I O, Pysmennyi S V and Kalinichenko O V 2019 *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu* **1** 37–41 URL https://doi.org/10.29202/nvngu/2019-1/20
[6] Khomenko O, Kononenko M, Kovalenko I and Astafiev D 2018 *E3S Web Of Conferences* **60**(6) 00009 URL http://doi.org/10.1051/e3sconf/20186000009
[7] Kononenko M and Khomenko O 2010 *New Techniques and Technologies in Mining - Proceedings of the School of Underground Mining* 193–197 URL http://doi.org/10.1201/b11329-32
[8] Petlovanyi M, Lozynskyi V, Zubko S, Saik P and Sai K 2019 *Rudarsko Geolosko Naftni Zbornik* **34**(1) 83–91 URL https://doi.org/10.17794/rgn.2019.1.8
[9] Pysmenniy S, Shvager N, Shepel O, Kovbyk K and O D 2020 *E3S Web of Conferences* **166** 02006 URL https://doi.org/10.1051/e3sconf/202016602006

[10] Morkun V, Morkun N and Tron V 2015 *Metallurgical and Mining Industry* **7**(7) 16–19 URL https://www.metaljournal.com.ua/assets/Journal/english-edition/MMI_2015_7/003Vladimir%20Morkun%2016-19.pdf
[11] Khomenko O, Tsendjav L, Kononenko M and Janchiv B 2017 *Mining Of Mineral Deposits* **11**(4) 86–95 URL http://doi.org/10.15407/mining11.04.086
[12] Khomenko O, Kononenko M and Netecha M 2016 *Mining of Mineral Deposits* **10**(1) 50–56 URL https://doi.org/10.15407/mining10.01.050
[13] Khomenko O and Kononenko M 2019 *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu* **3** 12–21 URL https://doi.org/10.29202/nvngu/2019-3/3
[14] Stupnik N I, Fedko M B, Kolosov V A and Pismennyy S V 2014 *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu* **5** 21–25 URL http://ds.knu.edu.ua/jspui/handle/123456789/3125
[15] Korniyenko V Y, Vasylchuk O Y, Zaiets V V, Semeniuk V V, Khrystyuk A O and Malanchuk Y Z 2022 *IOP Conference Series: Earth and Environmental Science* **1049**(1) 012027 URL https://doi.org/10.1088/1755-1315/1049/1/012027
[16] Malanchuk Y, Moshynskyi V, Khrystyuk A, Malanchuk Z, Korniienko V and Abdiev A 2022 *Mining of Mineral Deposits* **16**(1) 68–76 URL https://doi.org/10.33271/mining16.01.068
[17] Moshynskyi V S, Korniienko V Y, Malanchuk Ye Z A, Khrystyuk A O, Lozynskyi E C and Cabana E C 2021 *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetuthis link is disabled* **6** 35–41 URL https://doi.org/10.33271/nvngu/2021-6/035
[18] Tron V, Haponenko A, Haponenko I and Paranyuk D 2020 *E3S Web of Conferences* **201** 01025 URL https://doi.org/10.1051/e3sconf/202020101025
[19] Golik V, Morkun V, Morkun N and Gaponenko I 2018 *Mining of Mineral Deposits* **12**(3) 63–70 URL https://doi.org/10.15407/mining12.03.063
[20] Morkun V, Morkun N, Tron V, Serdiuk O and Dotsenko I 2019 *Archives of Acoustics* **44**(1) 161–167 URL http://ds.knu.edu.ua/jspui/handle/123456789/2114
[21] Kononenko M, Khomenko O, Savchenko M and Kovalenko I 2019 *Mining Of Mineral Deposits* **13**(3) 22–30 URL https://doi.org/10.33271/mining13.03.022
[22] Khomenko O, Rudakov D and Kononenko M 2011 *Technical And Geoinformational Systems In Mining* 271–275 URL http://doi.org/10.1201/b11586-45
[23] Myronova I 2016 *Mining of Mineral Deposits* **10**(2) 64–71 URL https://doi.org/10.15407/mining10.02.064
[24] Bazaluk O, Petlovanyi M, Lozynskyi V, Zubko S, Sai K and Saik P 2021 *Sustainability* **13**(2) 834 URL https://doi.org/10.3390/su13020834
[25] Bazaluk O, Petlovanyi M, Zubko S, Lozynskyi V and Sai K 2021 *Minerals* **11**(8) 858 URL https://doi.org/10.3390/min11080858
[26] Lyashenko V, Andreev B and Dudar T 2022 *Mining of Mineral Deposits* **16**(1) 43–51 URL https://doi.org/10.33271/mining16.01.043
[27] Lozynskyi V, Medianyk V, Saik P, Rysbekov K and Demydov M 2020 *Rudarsko Geolosko Naftni Zbornik* **35**(2) 23–32 URL https://doi.org/10.17794/rgn.2020.2.3
[28] Takhanov D, Muratuly B, Rashid Z and Kydrashov A 2021 *Mining of Mineral Deposits* **15**(1) 50–58 URL https://doi.org/10.33271/mining15.01.050
[29] Panchenko V, Sobko B, Lotous V, Vinivitin D and Shabatura V 2021 *Mining of Mineral Deposits* **15**(1) 87–95 URL https://doi.org/10.33271/mining15.01.087
[30] Zeylik B, Arshamov Y, Baratov R and Bekbotayeva A 2021 *Mining of Mineral Deposits* **15**(2) 134–142 URL https://doi.org/10.33271/mining15.02.134
[31] Nurpeissova M, Rysbekov K, Levin E, Derbisov K and Nukarbekova Z 2021 *Engineering Journal of Satbayev University* **143**(5) 3–9 URL https://doi.org/10.51301/vest.su.2021.i5.01
[32] M K and O K 2021 *Mining of Mineral Deposits* **15**(2) 111–123 URL https://doi.org/10.33271/mining15.02.111
[33] Myronova I 2015 The level of atmospheric pollution around the iron-ore mine *New Developments in Mining Engineering 2015: Theoretical and Practical Solutions of Mineral Resources Mining* p 193–197 URL https://doi.org/10.1201/b19901-35
[34] Rakishev B R, Auezova A M, Kuttybayev A Y and Kozhantov A U 2014 *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu* **6** 22–27 URL http://www.nvngu.in.ua/index.php/en/home/1008-engcat/archive/2014/contents-no-6-2014/geology/2854-specifications-of-the-rock-massifs-by-the-block-sizes
[35] Rysbekov K, Bitimbayev M, Akhmetkanov D, Yelemessov K, Barmenshinova M, Toktarov A and Baskanbayeva D 2022 *Mining of Mineral Deposits* **16**(2) 64–72 URL https://doi.org/10.33271/mining16.02.064

[36] Bazaluk O, Rysbekov K, Nurpeisova M, Lozynskyi V, Kyrgizbayeva G and Turumbetov T 2022 *Frontiers in Environmental Sciencey* **10** 852591 URL https://doi.org/10.3389/fenvs.2022.852591

[37] Issayeva L, Togizov K, Duczmal-Czernikiewicz A, Kurmangazhina M and Muratkhanov D 2022 *Mining of Mineral Deposits* **16**(2) 14–21 URL https://doi.org/10.33271/mining16.02.014

[38] Rylnikova M V and Mitishova N A 2021 *Engineering Journal of Satbayev University* **143**(4) 10–15 URL https://doi.org/10.51301/vest.su.2021.i4.02

[39] Imashev A, Suimbayeva A, Zhunusbekova G, Zeitinova S, Kuttybayev A and Mussin A 2022 *Mining of Mineral Deposits* **16**(3) 61–66 URL https://doi.org/10.33271/mining16.03.061

[40] Kovrov O, Babiy K, Rakishev B and Kuttybayev A 2016 *Mining of Mineral Deposits* **10**(2) 55–63 URL https://doi.org/10.15407/mining10.02.055

[41] Peregudov V, Hryhoriev I, Joukov S and Hryhoriev Y 2020 *E3S Web of Conferences* **166** 02004 URL https://doi.org/10.1051/e3sconf/202016602004

[42] Joukov S, Lutsenko S, Hryhoriev Y, Martyniuk M and Peregudov V 2020 *E3S Web of Conferences* **166** 02005 URL https://doi.org/10.1051/e3sconf/202016602005

[43] Azarian V, Lutsenko S, Zhukov S, Skachkov A, Zaiarskyi R and Titov D 2020 *Mining of Mineral Deposits* **14**(1) 1–10 URL https://doi.org/10.33271/mining14.01.001

[44] Stupnik M and Kalinichenko V 2013 *Annual Scientific-Technical Colletion - Mining of Mineral Deposits* pp 49–52 URL https://doi.org/10.1201/b16354-10

[45] Stupnik M, Kalinichenko V, Bah I, Pozdniakov V and Keita D 2014 *Progressive Technologies of Coal, Coalbed Methane, and Ores Mining* p 159–162 URL https://doi.org/10.1201/b17547

[46] Mironova I and Borysovs'ka O A 2014 Defining the parameters of the atmospheric air for iron ore mines *Progressive Technologies of Coal, Coalbed Methane, and Ores Mining* pp 333–340 URL https://doi.org/10.1201/b17547-57

[47] Petlovanyi M, Ruskykh V, Zubko S and Medianyk V 2020 *E3S Web of Conferences* **201** 01027 URL https://doi.org/10.1051/e3sconf/202020101027

[48] Petlovanyi M V, Zubko S A, Popovych V V and Sai K S 2020 *Voprosy Khimii i Khimicheskoi Technologii* **6** 142–150 URL https://doi.org/10.32434/0321-4095-2020-133-6-142-150

[49] Blizniukov V H and Lutsenko S O 2017 *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu* **1** 44–49

[50] Lutsenko S O 2017 *Quality – Access to Success* **18**(S1) 226–230 URL https://www.proquest.com/openview/87ac497268d7644e316b4c1bfc24d289/1.pdf?pq-origsite=gscholar&cbl=1046413

[51] Bolatova A, Kuttybayev A, Kainazarov A, Hryhoriev Y and Lutsenko S 2022 *Series of geology and technical sciences* **1** 33–38 URL https://doi.org/10.32014/2022.2518-170X.137

[52] Petlovanyi M and Mamaikin O 2019 *ARPN Journal of Engineering and Applied Sciences* **14**(20) 3492–3503 URL https://ir.nmu.org.ua/handle/123456789/154573

[53] Morkun V V, Fischerauer G, Morkun N, Tron V and Haponenko A 2022 Determining rock varieties on the basis of fuzzy clustering of ultrasonic measurement results *Proceedings of the 3rd International Workshop on Intelligent Information Technologies & Systems of Information Security, Khmelnytskyi, Ukraine, March 23-25, 2022* (*CEUR Workshop Proceedings* vol 3156) ed Hovorushchenko T, Savenko O, Popov P T and Lysenko S (CEUR-WS.org) pp 274–283 URL https://ceur-ws.org/Vol-3156/paper20.pdf

[54] Golik V, Komashchenko V, Morkun V and Zaalishvili V 2015 *Metallurgical and Mining Industry* **7**(4) 325–329 URL https://www.metaljournal.com.ua/assets/MMI_2014_6/MMI_2015_4/047-GolikKomashchenkoMorkunZaalishvili.pdf

[55] Krupnik L, Yelemessov K, Bortebayev S and Baskanbayeva D 2018 *Eastern-European Journal of Enterprise Technologies* **6**(12-96) 22–27 URL https://doi.org/10.15587/1729-4061.2018.151038

[56] Baskanbayeva D D, Krupnik L A, Yelemessov K K, Bortebayev S A and Igbayeva A E 2020 *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu* **5** 68–74 URL https://doi.org/10.33271/NVNGU/2020-5/068

[57] Yelemessov K, Nauryzbayeva D, Bortebayev S, Baskanbayeva D and Chubenko V 2021 *E3S Web of Conferences* **280** 07007 URL https://doi.org/10.1051/e3sconf/202128007007

[58] Malanchuk Y, Moshynskyi V, Denisyuk P, Malanchuk Z, Khrystyuk A, Korniienko V and Martyniuk P 2021 *Mining of Mineral Deposits* **15**(1) 66–74 URL https://doi.org/10.33271/mining15.01.066

[59] Matheron G 1963 *Economic Geology* **58**(8) 1246–1266 URL https://doi.org/10.2113/gsecongeo.58.8.1246

[60] Matheron G 1967 *CIMM Transactions* **70** 240–244 URL http://www.cg.ensmp.fr/bibliotheque/public/MATHERON_Publication_00102.pdf

[61] David M 1980 *Geostatisticheskiye metody pri otsenke zapasov rud* Advanced Geostatistics in the Mining Industry (Leningrad: Nedra)

[62] Bukrinsky V A 1985 *Geometriya nedr* (Moscow: Nedra)

[63] Kim H S, Chung C K and Kim J J 2018 *Quarterly Journal of Engineering Geology and Hydrogeology* **51**(1) 79–95 URL https://doi.org/10.1144/qjegh2016-012

[64] Fedorenko P Y, Peremetchik A V, Podoynitsina T O and Nastin P V 2016 *Girnichy visnik* **109** 7–14
[65] Peremetchyk A V 2004 *Razrabotka rudnykh mestrozhdeniy* **10** 194–200
[66] Pysmennyi S, Peremetchyk A, Chukharev S, Fedorenko S, Anastasov D and Tomiczek K 2022 *IOP Conference Series: Earth and Environmental Science* **1049**(1) 012029 URL https://doi.org/10.1088/1755-1315/1049/1/012029
[67] Peremetchyk A, Kulikovska O, Shvaher N, Chukharev S, Fedorenko S, Moraru R and Panayotov V 2022 *Mining of Mineral Deposits* **16**(3) 67–77 URL https://doi.org/10.33271/mining16.03.067

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A new approach to producing a prospective energy resource based on coalmine methane

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A new approach to producing a prospective energy resource based on coalmine methane

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Abstract. The paper describes topical issues of a prospective method for coalmine methane utilization for obtaining an additional valuable energy resource for the regional development of coal-mining areas. It is noted that the development of the extraction of methane resources is very urgent and is of great economic importance for ensuring the energy independence of Ukraine. The experience and technologies of using methane and coalmine gas by global coal-mining companies are analyzed. Modern prospects and opportunities for using coal gas are studied. There is a need to transform the coalmine methane removal system and directions for maximizing the use of its resources in a wide range of concentrations in the composition of gas-air mixtures based on the development of innovative technologies to improve the efficiency and cost-effectiveness of functioning coal-mining enterprises. Attention is focused on the advantages of using gas hydrate technologies for obtaining additional energy resource under conditions of changing coalmine methane concentrations. The specifics of the process of mixed gas hydrate formation from gas mixtures of various geneses have been studied. It has been revealed that it is the coalmine gas-methane composition that determines and forms the basic condition for hydrate formation. The thermobaric conditions for the hydrate formation process at different methane concentrations in gas mixtures of degassing systems have been experimentally determined. The results obtained are the basis for further research on efficiency of creating gas hydrates from coalmine methane and determining its minimum permissible concentration in the gas mixture of degassing systems according to the technological and economic criteria of hydrate formation.

1. Introduction

Rational use of natural resources is the main prerequisite for ensuring sustainable social and economic development [1, 2]. In this regard, state regulation of resource consumption as a tool for environmental management is of great importance in most countries of the world, which is evidenced by a number of international agreements adopted within the framework of the United Nations. For Ukraine, such a tool can be not only the transformation of the coal industry, but also the reduction of operational losses of energy resources of coal-mining and coal-processing enterprises by involving in the economic turnover of associated resources of gas-coal deposits. As for today, coal, oil and natural gas continue to be the main fuel and energy resources [3–7].

In recent years, the energy market has undergone significant changes, which are primarily caused by the ever-increasing needs of society for energy, due to economic and technological development. Leading countries are beginning to fight for the right to develop energy resource deposits on neutral Arctic and Antarctic territories. More stringent environmental regulations are becoming an impetus for the transition to cleaner fuel types [8, 9]. There is a need to search for new alternative energy sources and develop technologies for their mining and use, as well as to improve the efficiency of existing technologies in the energy sector [10–12]. Thus, ensuring energy security is becoming an increasingly complex and multifaceted task.

According to existing predictions and reports, energy consumption is growing every year. Thus, in 2021, the global demand for electricity increased by almost 50% [13]. Analyzing the World Energy Outlook report for 2022, the situation has almost remained unchanged, demand continues to rise, but at a somewhat slower pace, given today's high prices for energy carriers and market instability due to Russia's aggression on the territory of Ukraine [14]. Having faced with market uncertainty and high prices, consumers are withdrawing some of their gas purchases, and industry is reducing production. Despite a strong post-pandemic economic recovery in 2021, the average annual GDP growth rate for the rest of the decade assumed by the Stated Policies Scenario in 2020 has been slightly revised. As a result, energy demand is growing at a slower pace and the fuels used to meet this demand growth are different from previous projections (figure 1) [14].

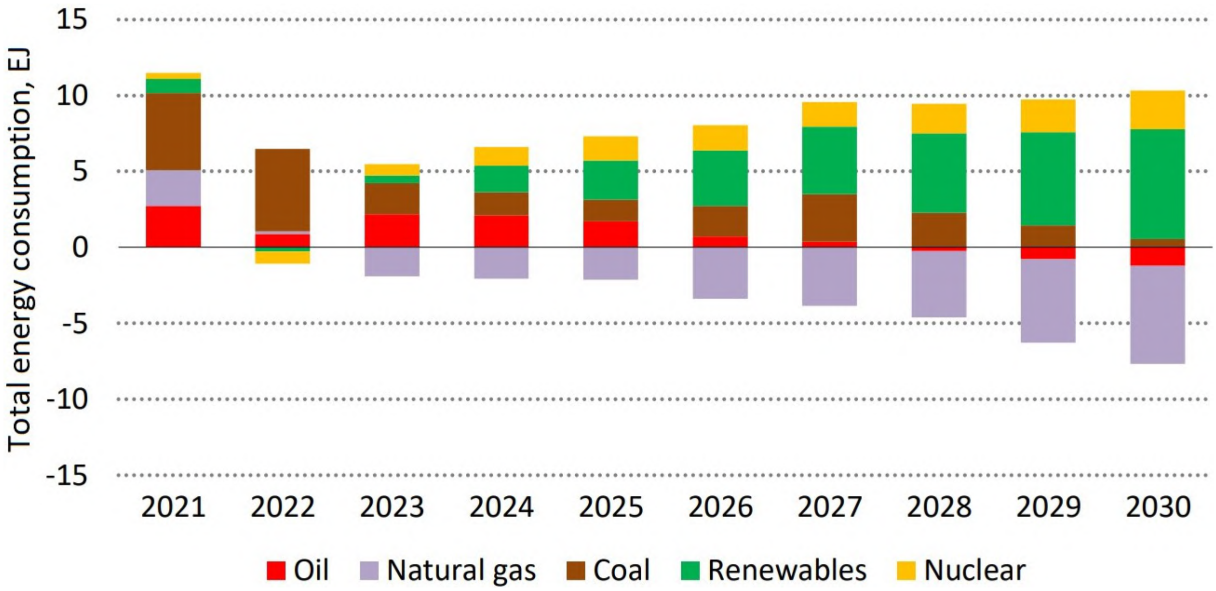

Figure 1. Predicted global consumption of fuel and energy resources [14].

As it can be seen, in the context of the diversification of hydrocarbon sources and the war unleashed by Russia in Ukraine, an unstable situation has developed on the global fuel and energy market. Of particular importance is the issue of determining the energy security prospects of many countries, including Ukraine, by increasing the volumes of domestic gas production or searching for renewable and alternative fuel types [15, 16]. Despite the significant potential of the major types of renewable energy sources, their practical use today is only a small part in the fuel-energy balance (figure 1). Nevertheless, the interest in the development of production technologies for new types of energy raw materials is increasing significantly. Currently, alternative types of gas fuel include methane from coal deposits and coalmine methane [17]; gas obtained from the processing of solid fuel (hard and brown coal, oil shale, peat) [18, 19]; producer gas, other gaseous fuel derived from biological raw materials [20]. Special attention should be paid to the development and implementation of gas production technologies by underground coal gasification [21, 22]. However, according to many scientists, the most promising source of hydrocarbon fuels are gas hydrate deposits found in many countries of the world [23–29].

On an industrial scale, methane is not produced from gas hydrate deposits in the world today.

However, a number of leading countries, such as Japan, the USA, Canada, India, China, Norway, South Korea, Australia, Turkey, Bulgaria and Ukraine, are implementing large-scale research programs and are actively engaged in studying the issue of gas hydrates, both artificial and natural, as well as in the development of hydrate formation and dissociation technologies [30–36]. Assessment of the economic efficiency of gas hydrate projects requires certain clarifications. This uncertainty is aggravated by the ongoing search for both optimal technologies for the development of gas hydrate deposits, as well as obtaining gas hydrates for their use when transporting hydrocarbon raw materials.

Obviously, natural gas remains the most commercially prepared energy carrier [37]. Therefore, consideration of issues related to the development of hydrocarbons [38–40] and the industrial utilization of natural reserves of methane – the most demanded fuel in Ukraine – is extremely relevant and is of great economic importance for ensuring the energy independence of our country [41, 42].

2. Prospects and opportunities of using coal gas

Given the interest in non-conventional energy sources, more and more attention has recently been paid to coal seam gas, which can be extracted by implementing innovative coal-mining technologies. The successful experience of gas companies in the United States has even led to the announcement of the creation of a gas subsector dedicated to the methane production from coal seams [43–45]. By combining the interests of the gas and coal industries, it is possible to ensure and significantly improve the technical, economic, ecological and social conditions of the population in industrial regions.

Over the past 15-20 years, this area has received significant attention and intensive development in the United States, where the average volume of gas production from coal seams is 55 billion m^3 annually, in Canada – more than 9 billion m^3, in Australia – 5.5 billion m^3, in China – 1.2 billion m^3, Russia – 6 million m^3 [46–48].

Natural gas from coal seams is 90% or more methane. Methane is the purest hydrocarbon energy source with almost no harmful impurities, such as nitrogen or sulphur compounds. Currently, commercial production of methane from coal seams is carried out only in the United States. Over 9 thousand wells are in operation, of which more than 40% are located in the San Juan Basin. About 10% of wells in this basin provide 75% of its production and 60% of the total annual coalmine methane production in the United States [49, 50].

Also, in recent years, technologies for using ventilation gas removed from the mine along with the ventilation air flow have gained significant development. The first major project of this kind in the world is the Australian West Cliff Ventilation Air Methane Project (WestVAMP), which converts a part of the ventilation jet into heat and electricity using the VOCSIDIZER™ energy system from the Megtec Company (Sweden) [51]. This technology involves the use of ventilation gas with an extremely low methane concentration of 0.3-1.2%, but requires further improvement due to low economic efficiency. The Natural Resources Company (Canada) developments use reverse-flow reactors (Catalytic Flow Reversal Reactor, CFRR), which are also designed to generate heat by utilizing an off-standard gas mixture with 0.5-1.0% methane content [52].

When mining coal deposits, outgoing gas-air flows occur, which are formed in the process of diluting the released gas with atmospheric air and methane-air mixture sucked from the mined-out area and drilled wells in the coal-rock mass (figure 2) [53]. Under the conditions of high methane-bearing capacity of coal deposits, degassing is the main way of ensuring the coal-mining safety. Therefore (regardless of other possibilities of using the methane-air mixture), the main condition remains the extraction of gas from the coal-rock mass and the mined-out area, its localization and removal to the surface or to the outgoing jet.

In Ukraine, coal mines emit most of the methane (up to 90%) into the atmosphere in the form of a low-concentration gas-air mixture from mine ventilation units. In 2016, about 517

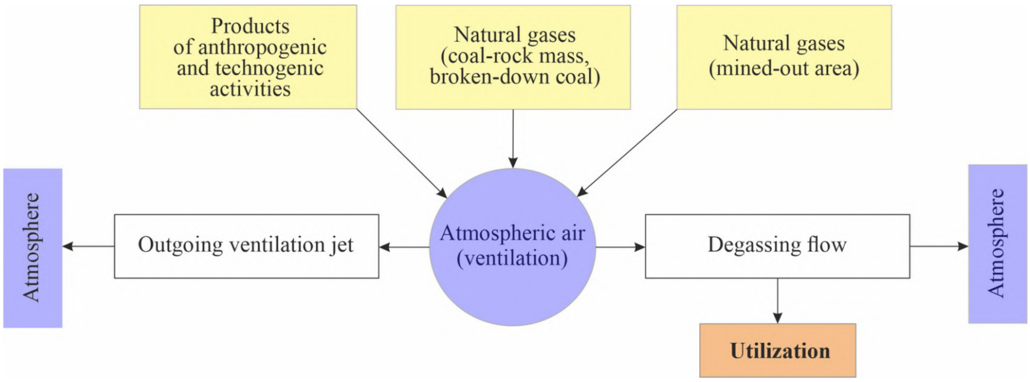

Figure 2. Scheme of formation of the outgoing gas-air flows [53].

million m^3 of methane gas was released during coal mining by 50 mines [54], which is equivalent to the production of 3.3 billion kWh or 3.0 billion m^3 of burned natural gas and exceeds the electricity consumption of all coal-mining enterprises in Ukraine. In global practice, mixtures with a methane concentration above 25-50% are most efficiently utilized. Therefore, it can be concluded that the energy potential of coalmine gas-methane during mining operations is extracted from the bowels, and its potential is not fully utilized for the needs of industry and the population.

Thus, in the conditions of the most powerful coal-mining enterprise in Ukraine, PJSC Mine Administration "Pokrovske", a universal combined degassing method is used – underground method, which extracts about 60% of coal methane, and degassing from the surface, extracting 40% of methane. The underground degassing system is represented by a network of degassing pipelines in mine workings, through which, using two vacuum-pump stations on the surface, coalmine methane is extracted through drilled wells from the mined-out area and the coal mass of the extraction sites. The methane concentration in the gas-air mixture during underground degassing varies widely, ranging from 15 to 70%. Surface degassing involves drilling degassing wells every 300 m in extraction panels ahead of the stoping faces in highly stressed longwall faces. The methane concentration in the gas-air mixture with this method is extremely high, since the mass is not de-stressed and ranges between 90-98%. For gas utilization, a cogeneration plant with a capacity of 18 MW has been implemented at the enterprise, but only up to 40% of methane is utilized, because its flow rate and concentrations are variable, making it difficult to utilize it.

In most other coal mines in Ukraine, coal methane is currently extracted to the surface as part of ventilation jets and underground degassing systems. In this case, the methane-air mixture coming to the surface is usually substandard and is released into the atmosphere or burned. Only if the methane content in the gas-air mixture exceeds 25%, it becomes possible to use cogeneration plants. Thus, at the Stepova mine (PJSC "DTEK Pavlohradvuhillia") for a year, about 6 million kW of electricity has been generated from 1.3 million m^3 of extracted coalmine methane using a cogeneration plant [55].

In this regard, the problem of the large scale of coalmine gas utilization is becoming increasingly important, the great difficulties of which are associated with the variability of its flow rates and the different methane content in the extracted mixtures, as well as the limitated possibility of using cogeneration plants to generate electrical or thermal energy [56, 57].

Therefore, today it is required to transform the coalmine methane removal system and the directions for maximizing the use of its resources in a wide range of concentrations in the composition of gas-air mixtures (15-98%) based on the development of innovative technologies to improve the efficiency and cost-effectiveness of functioning coal-mining enterprises.

3. Advantages of using gas hydrate technologies for obtaining additional energy resource

As a result of significant variations in methane concentration in the gas mixtures of degassing wells, its widespread use is becoming more difficult. Therefore, it becomes necessary to create a method for producing methane in the final chain of mining gas-coal deposits, for which the component composition of the outgoing gas would not be a stringent condition. This method, according to the authors, is the conversion of gas into a solid gas-hydrate state, since gas-hydrate technology makes it possible to convert various gases into hydrates, including their mixtures. In this case, only the equilibrium conditions of the hydrate formation process will change [58, 59]. It is easier and safer to store and transport methane in the state of gas hydrates to industrial and energy companies for its further use as an energy carrier, which is another advantage of gas hydrate technologies [60, 61].

Hydrates are formed and stably exist in a wide range of thermobaric parameters. But each individual gas is characterized by certain variants of pressures and temperatures of the hydrate phase stability existence. The main factors determining the conditions for hydrate formation and storage of gas hydrates, first of all, should be considered the composition of gases, their moisture saturation, phase state, composition and state of water, its mineralization, external pressure and temperature [62]. The gas composition determines the basic condition for hydrate formation – the higher the molecular weight of an individual gas or mixture of gases, the lower the pressure required for hydrate formation at the same temperature. Natural gases, consisting of a combination of individual components, form mixed gas hydrates. In this case, during hydrate formation, crystals are simultaneously formed, which are characteristic of both methane and other hydrocarbon and associated gases in the mixture. That is, for the conditions of gas-air mixtures of degassing systems in coal mines, it is possible to apply the concept of mixed gas hydrates.

The following characteristic stages are distinguished during hydrate formation:

1) formation of gas hydrate crystallization centers;
2) sorption growth of crystalline hydrates around crystallization centers;
3) mass crystallization or simultaneous increase of a large number of formed crystallization centers.

Further in the research, the possibility of creating methane gas hydrates from degassing gas mixtures of a coal mine with a wide variation of methane concentrations is experimentally studied.

4. Research methods

The conversion of methane-air mixtures of degassing systems into the gas-hydrate state, when mining gas-coal deposits, would solve a number of difficulties related to their utilization and subsequent use. However, the specificity of the component composition of gas mixtures necessitate the development of optimal parameters for the hydrate formation process. The process of nucleation and formation of gas hydrates from gas mixtures of various geneses is more complex than from individual gases, which manifests itself in the changing value of equilibrium parameters for hydrate formation and its rate.

In order to determine the patterns of the hydrate formation process and the influence of various technological and regime parameters on it, a bench unit has been developed, consisting of an ILKA KTK-3000 Climatic-Thermal Chamber and a number of other measuring equipment. The Climatic-Thermal Chamber allows conducting research in different temperature conditions and with different humidity. Structurally, the Climatic-Thermal Chamber has four main parts:

the working volume, in which the NPO-5 hydrate formation reactor is directly located, the automatic control panel, the refrigeration unit and the steam generator. The NPO-5 unit is equipped with a reducer, which makes it possible to regulate the pressure of the gas mixture from 0 to 10 MPa and maintain it constant throughout the entire duration of the experiment [63].

A transparent polymer pipe with a wall thickness of 2.5 mm is used for conducting experimental research and visual observation of the hydrate formation and hydrate accumulation processes. To record the pressure and velocity of the water and gas flowing out of the high-pressure nozzles, the unit is equipped with a measuring system consisting of a direct-acting indicating pressure gauge, a thermometer, an anemometer and a PC-based measuring station. To conduct experimental research on the process of hydrate formation from gas mixtures, jet-forming nozzles of an original design are used.

5. Research results

For reasons of clarity of the experiment and the comparison of the obtained further results, the process of hydrate formation from pure methane is studied as a standard at the first stage, the actual volume fraction of which is 99.7%. The hydrate formation curve and process parameters are given in figure 3.

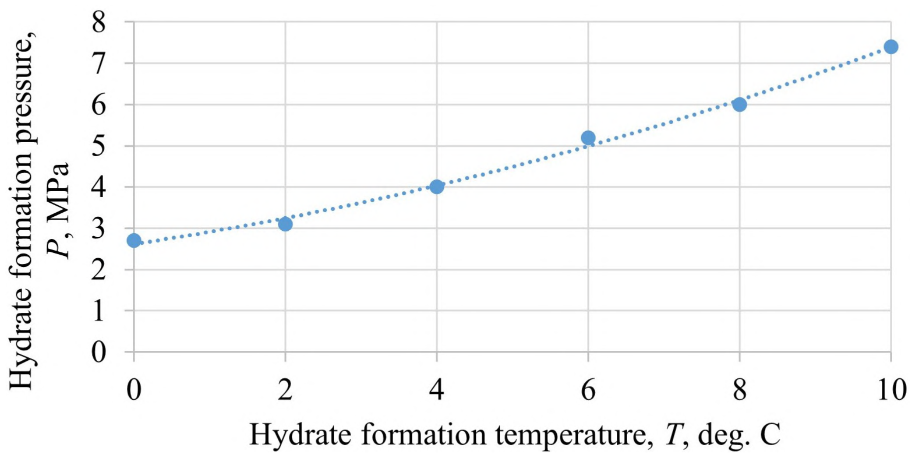

Figure 3. Parameters of the methane hydrate formation process.

The resulting pattern of methane gas hydrate formation (Fig. 3) has a polynomial character with the value of approximation reliability $R^2 = 0.99$ and is described by the equation $y = 0.02x^2 + 0.27x + 2.62$. The pressure range varies from 3 to 7.5 MPa. This has experimentally proven the fact that at pressures below 3 MPa, the hydrate formation process using pure methane is difficult and requires a sufficiently long time to start crystallization with the formation of crystalline hydrate nuclei (according to existing data, up to several days). Accordingly, it is inexpedient to conduct research under such pressures. The increase in temperature parameters occurs naturally with increasing pressure and reaches its maximum value at +10°C.

In order to study the influence of thermobaric parameters on the conditions for the formation of gas hydrates, depending on methane concentration in gas mixtures of degassing systems, samples have been taken directly from the Western Donbas coal-mining enterprises. Their compositions are given in table 1.

The thermobaric parameters of the hydrate formation process from gas mixtures of degassing systems have been obtained experimentally (figure 4). Methane concentrations in the selected mixtures range from 47 to 95%, reflecting their real wide variation with degassing methods in

Table 1. Compositions of gas mixtures obtained from degassing systems.

No.	Methane	Ethane	Propane	Butane	Carbon dioxide	Nitrogen
Mixture 1	0.95	0.02	0.025	–	0.005	–
Mixture 2	0.86	0.06	0.04	0.01	–	0.03
Mixture 3	0.75	0.06	0.04	–	0.01	0.14
Mixture 4	0.54	0.15	–	–	0.21	0.10
Mixture 5	0.47	0.08	0.07	–	0.33	0.05

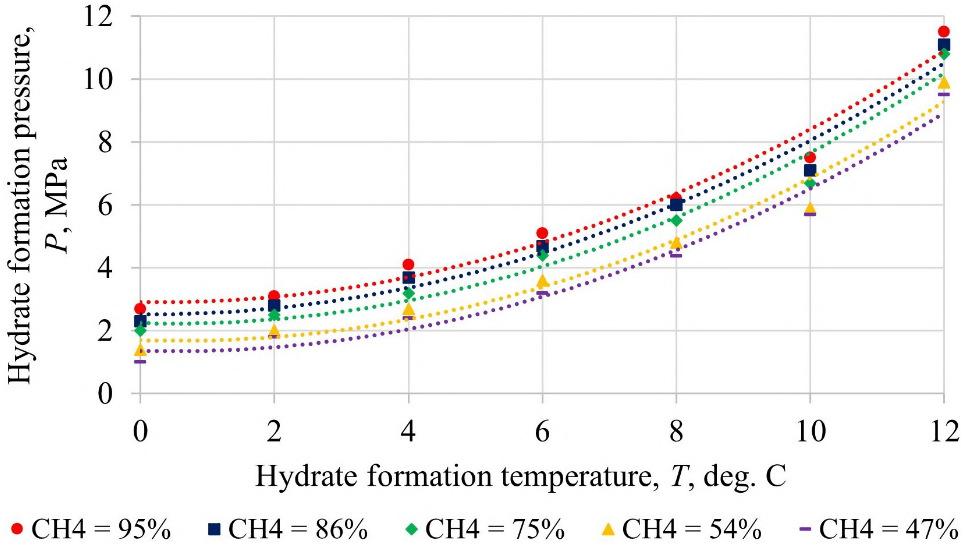

Figure 4. Parameters of hydrate formation of gas mixtures in degassing systems in the Western Donbas mines.

coal mine conditions. The resulting dependences of pressure on temperature change according to a polynomial law with an approximation value of $R^2 = 0.97$ for each separately selected mixture.

At the same time, the highest pressures of hydrate formation are for a mixture with a methane concentration of 95%, and the lowest, respectively, for a mixture with 47% methane in the gas mixture (figure 4).

The patterns of the gas hydrate formation process from mixtures of various genesis, depending on pressure and temperature, are described by the following equations:

– at $CH_4 = 47\% - y = 0.06x^2 - 0.06x + 1.37$;
– at $CH_4 = 54\% - y = 0.06x^2 - 0.07x + 1.70$;
– at $CH_4 = 75\% - y = 0.06x^2 - 0.06x + 2.25$;
– at $CH_4 = 86\% - y = 0.06x^2 - 0.02x + 2.53$;
– at $CH_4 = 95\% - y = 0.06x^2 - 0.04x + 2.92$.

Also, the formation parameters of mixed gas hydrates are influenced by the presence of carbon dioxide in the mixture, in addition to hydrocarbon gases. It has been found in the previous research that the pressure required to form carbon dioxide hydrates is by 20-30% lower than for methane hydrates, depending on the conditions of hydrate formation. This fact is also observed during the formation of mixed gas hydrates, although the CO_2 share in the mixtures is quite low.

In the future, for the production of gas hydrates from coalmine methane, it is proposed to build a hydrate formation complex near the facilities of degassing systems in the surface mine complex, followed by their transportation by mobile refrigerators to consumers (industry, population, etc.) and settlements located near the coal mine.

To evaluate the economic efficiency of the proposed technological solutions in the future, it is planned to use the methods of economic and mathematical modeling, taking into account the capital investments in equipment, the cost of the final product, the determination of operating costs, the reduction of charges for atmospheric pollution, the level of consumption by the population or industrial enterprises of gas obtained by the gas hydrate method.

6. Conclusions

The energy market has undergone significant changes in recent years, which are caused by the growing needs of society for energy resources. In the context of diversification of hydrocarbon sources, the issue of ensuring the energy security of many countries of the world and Europe is of great importance. This encourages the search for new alternative energy sources and the development of innovative technologies, in particular, gas hydrate technologies.

The prospects and possibilities of using coal gas in the implementation of innovative technologies for mining gas-coal deposits have been studied. The experience and technologies of using methane and coalmine gas by global coal-mining companies have been analyzed. The experience of many American enterprises and companies has even made it possible to declare the formation of a gas subsector dedicated to the methane production from coal seams. The experience of Australia and Canada on the use of ventilation gas carried out of the mine together with the ventilation air flow has been studied.

The experience of using degassing systems at Ukraine's largest coal enterprise PJSC Mine Administration "Pokrovske", which uses both underground degassing and surface degassing methods, has been analyzed. For gas utilization, a cogeneration plant has been implemented at the enterprise, but only up to 40% of methane is utilized, because its flow rate and concentrations are variable, making it difficult to utilize it. Thus, in most other coal mines in Ukraine today, the methane-air mixture coming to the surface is usually substandard and is released into the atmosphere or burned. Therefore, it becomes necessary to create a method for producing methane in the final chain of mining gas-coal deposits, for which the component composition of the outgoing gas would not be a stringent condition. This method is the implementation of gas hydrate technologies for obtaining the final product.

The main factors influencing the conditions for the hydrate formation process and storage of gas hydrates, as well as their thermobaric parameters have been determined, which should be further taken into account when developing a technological scheme for the utilization of methane mixtures. The specifics of the process of mixed gas hydrate formation from gas mixtures of various geneses have been studied. It has been revealed that it is gas composition that determines the basic condition for hydrate formation.

A number of experimental researches on the process of obtaining gas hydrates from methane-air mixtures of various geneses have been conducted. In addition, the peculiarities of hydrate formation, which are typical for the formation of mixed gas hydrates, have been determined. For reasons of clarity of the experiment, the process of hydrate formation from pure methane has been studied as a standard, the actual volume fraction of which is 99.7%. The hydrate formation pressure varies in the range of 3.0-7.5 MPa, since at pressures lower than 3.0 MPa, the process of crystal hydrate nuclei formation takes a long time.

The thermobaric conditions have been determined for the hydrate formation process at various methane concentrations in gas mixtures of degassing systems (47-95%), indicating their wide variation depending on the method of degassing in different coal mines. The dependence of the methane concentration on the hydrate formation pressure has been revealed: the higher the CH_4 concentration in the mixture, the higher the gas hydrate formation pressure should be.

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References

[1] Moitra A K, Bhattacharya J, Kayal J R, Mukerji B and Das A K (eds) 2021 *Innovative Exploration Methods for Minerals, Oil, Gas, and Groundwater for Sustainable Development* (Elsevier)
[2] Khorolskyi A, Mamaikin O, Medianyk V, Lapko V and Sushko V 2021 *ARPN Journal of Engineering and Applied Sciences* **16**(18) 1890–1899 URL https://www.researchgate.net/publication/357183248
[3] Court V and Fizaine F 2017 *Ecological Economics* **138** 145–159 ISSN 0921-8009 URL https://doi.org/10.1016/j.ecolecon.2017.03.015
[4] Li C M, Cui T, Nie R, Lin H and Shan Y 2019 *Resources Policy* **61** 88–98 ISSN 0301-4207 URL https://doi.org/10.1016/j.resourpol.2019.01.013
[5] Blazev A S 2015 *Energy security for the 21st century* (River Publishers)
[6] Pysmennyi S, Peremetchyk A, Chukharev S, Fedorenko S, Anastasov D and Tomiczek K 2022 *IOP Conference Series: Earth and Environmental Science* **1049**(1) 012029 URL https://doi.org/10.1088/1755-1315/1049/1/012029
[7] Sakhno I, Sakhno S and Vovna O 2020 *Mining of Mineral Deposits* **14**(1) 72–80 URL https://doi.org/10.33271/mining14.01.072
[8] Stefanakos E K and Srinivasan S S (eds) 2019 *Clean Energy and Fuel (Hydrogen) Storage* (MDPI) URL https://doi.org/10.3390/books978-3-03921-6431-4
[9] Twidell J 2021 *Renewable Energy Resources* 4th ed (Routledge)
[10] Abas N, Kalair A and Khan N 2015 *Futures* **69** 31–49 ISSN 0016-3287 URL https://doi.org/10.1016/j.futures.2015.03.003
[11] Rizakulyevna C M 2021 *The American Journal of Applied Sciences* **3**(01) 58–68 URL https://doi.org/10.37547/tajas/Volume03Issue01-11
[12] da Rosa A V and Ordonez J C 2021 *Fundamentals of Renewable Energy Processes* 4th ed (Elsevier)
[13] 2021 World Energy Outlook 2021 Tech. rep. International Energy Agency URL https://iea.blob.core.windows.net/assets/4ed140c1-c3f3-4fd9-acae-789a4e14a23c/WorldEnergyOutlook2021.pdf
[14] 2022 World Energy Outlook 2022 Tech. rep. International Energy Agency URL https://iea.blob.core.windows.net/assets/830fe099-5530-48f2-a7c1-11f35d510983/WorldEnergyOutlook2022.pdf
[15] Ovetska O, Ovetskyi S and Vytiaz O 2021 *E3S Web of Conferences* **230** 01021 URL https://doi.org/10.1051/e3sconf/202123001021
[16] Sabishchenko O, Rębilas R, Sczygiol N and Urbański M 2020 *Energies* **13**(7) 1776 URL https://doi.org/10.3390/en13071776
[17] Koroviaka Y, Pinka J, Tymchenko S, Rastsvietaiev V, Astakhov V and Dmytruk O 2020 *Mining of Mineral Deposits* **14**(3) 21–27 URL https://doi.org/10.33271/mining14.03.021
[18] Bondarenko V I, Kharin Y N, Antoshchenko N I and Gasyuk R L 2013 *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu* **5** 24–30
[19] Antoshchenko M, Tarasov V, Rudniev Y and Zakharova O 2022 *Mining of Mineral Deposits* **16**(2) 7–13 URL https://doi.org/10.33271/mining16.02.007
[20] Vera D, de Mena B, Jurado F and Schories G 2013 *Applied Thermal Engineering* **51**(1) 119–129 ISSN 1359-4311 URL https://doi.org/10.1016/j.applthermaleng.2012.09.012
[21] Lozynskyi V, Dichkovskiy R, Saik P and Falshtynskyi V 2018 *Solid State Phenomena* **277** 66–79 URL https://doi.org/10.4028/www.scientific.net/SSP.277.66
[22] Saik P and Berdnyk M 2022 *Mining of Mineral Deposits* **16**(2) 87–94 URL https://doi.org/10.33271/mining16.02.087
[23] Yu Y S, Zhang X, Liu J W, Lee Y and Li X S 2021 *Energy Environ. Sci.* **14**(11) 5611–5668 URL http://dx.doi.org/10.1039/D1EE02093E
[24] Klymenko V, Ovetskyi S, Vytyaz O, Uhrynovskyi A and Martynenko V 2022 *Mining of Mineral Deposits* **16**(3) 11–17 URL https://doi.org/10.33271/mining16.03.011
[25] Shnyukov Y F and Kobolev V 2017 *Geology and Mineral Resources of World Ocean* **13**(3) 5–23 URL https://doi.org/10.15407/gpimo2017.03.005
[26] Yamamoto K, Boswell R, Collett T S, Dallimore S R and Lu H 2021 *Energy and Fuels* **36**(10) 5047–5062 URL https://doi.org/10.1021/acs.energyfuels.1c04119

[27] Wallmann K and Schicks J M 2018 Gas Hydrates as an Unconventional Hydrocarbon Resource *Hydrocarbons, Oils and Lipids: Diversity, Origin, Chemistry and Fate* ed Wilkes H (Cham: Springer International Publishing) pp 1–17 ISBN 978-3-319-54529-5 URL https://doi.org/10.1007/978-3-319-54529-5_20-1
[28] Nair V C, Gupta P and Sangwai J S 2018 Gas Hydrates as a Potential Energy Resource for Energy Sustainability *Sustainable Energy Technology and Policies: A Transformational Journey, Volume 1* ed De S, Bandyopadhyay S, Assadi M and Mukherjee D A (Singapore: Springer Singapore) pp 265–287 ISBN 978-981-10-7188-1 URL https://doi.org/10.1007/978-981-10-7188-1_12
[29] Ganushevych K and Sai K 2020 *E3S Web of Conferences* **201** 01023 URL https://doi.org/10.1051/e3sconf/202020101023
[30] Makogon Y F, Holditch S A and Makogon T Y 2007 *Journal of Petroleum Science and Engineering* **56**(1) 14–31 ISSN 0920-4105 Natural Gas Hydrate / Clathrate URL https://doi.org/10.1016/j.petrol.2005.10.009
[31] Demirbas A 2010 *Energy Conversion and Management* **51**(7) 1562–1571 ISSN 0196-8904 URL https://doi.org/10.1016/j.enconman.2010.02.014
[32] Sain K and Gupta H 2012 *Gondwana Research* **22**(2) 645–657 ISSN 1342-937X Plate Tectonics of Asia: Geological and Geophysical Constraints URL https://doi.org/10.1016/j.gr.2012.01.007
[33] Boswell R, Hancock S, Yamamoto K, Collett T, Pratap M and Lee S R 2020 6 - Natural Gas Hydrates: Status of Potential as an Energy Resource *Future Energy* ed Letcher T M (Elsevier) pp 111–131 3rd ed ISBN 978-0-08-102886-5 URL https://doi.org/10.1016/B978-0-08-102886-5.00006-2
[34] Shaibu R, Sambo C, Guo B and Dudun A 2021 *Advances in Geo-Energy Research* **5**(3) 318–332 URL https://doi.org/10.46690/ager.2021.03.07
[35] Zhu Y, Wang P, Pang S, Zhang S and Xiao R 2021 *Energy and Fuels* **35**(11) 9137–9150 URL https://doi.org/10.1021/acs.energyfuels.1c00485
[36] Bazaluk O, Sai K, Lozynskyi V, Petlovanyi M and Saik P 2021 *Energies* **14**(5) 1345 URL https://doi.org/10.3390/en14051345
[37] Leung G C K 2015 Natural Gas as a Clean Fuel *Handbook of Clean Energy Systems* (John Wiley & Sons, Ltd) pp 1–15 ISBN 9781118991978 URL https://doi.org/10.1002/9781118991978.hces055
[38] Kotarba M J and Koltun Y V 2006 The Origin and Habitat of Hydrocarbons of the Polish and Ukrainian Parts of the Carpathian Province *The Carpathians and Their Foreland: Geology and Hydrocarbon Resources* (American Association of Petroleum Geologists) ISBN 9781629810379 URL https://doi.org/10.1306/985605M843074
[39] Krupskyi Y Z 2018 *Geological Journal* **2**(0) 5–13 URL https://doi.org/10.30836/igs.1025-6814.2018.2.133390
[40] Rudko G and Sobol V 2020 *Mineral Resources of Ukraine* (2) 36–42 URL https://doi.org/10.31996/mru.2020.2.36-42
[41] Chukharev S M, Lozynskyi V H, Zaiets V V, Solvar L M and Okseniuk R R 2021 Prospects of methane mining in the Western region of Ukraine *Energy-and Resource-Saving Technologies of Developing the Raw-Material Base of Mining Regions* (Petroșani, Romani: UNIVERSITAS Publishing) pp 104–121 URL https://ep3.nuwm.edu.ua/20350/
[42] Perov M O and Novytskyi I Y 2021 *System Research in Energy* (4 (67)) 30–39 URL https://doi.org/10.15407/pge2021.04.030
[43] Wise R L and Rightmire C T 1979 Methane Recovery And Utilization From Coalbeds *SPE Annual Technical Conference and Exhibition* pp SPE–8357–MS URL https://doi.org/10.2118/8357-MS
[44] Rightmire C T, Eddy G E and Kirr J N 1984 *Coalbed Methane Resources of the United States* (American Association of Petroleum Geologists) ISBN 9781629811635 URL https://doi.org/10.1306/St17437
[45] Hanushevych K and Srivastava V 2017 *Mining of Mineral Deposits* **11**(3) 23–34 URL https://doi.org/10.15407/mining11.03.023
[46] Creedy D and Tilley H 2003 *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy* **217**(1) 19–25 URL https://doi.org/10.1243/095765003321148655
[47] Zhou F, Xia T, Wang X, Zhang Y, Sun Y and Liu J 2016 *Journal of Natural Gas Science and Engineering* **31** 437–458 ISSN 1875-5100 URL https://doi.org/10.1016/j.jngse.2016.03.027
[48] Drizhd N A, Kamarov R K, Akhmatnurov D R, Zamaliyev N M and Shmidt-Fedotova I M 2017 *Scientific Bulletin of National Mining University* (1) 12–20 URL https://tinyurl.com/5278yjmu
[49] Parker J M, Riggs E A and Fisher W L 1977 Oil and gas potential of the San Juan basin *Guidebook of San Juan Basin III: New Mexico Geological Society, 28th FC* ed Fassett J E, James H L and Hodgson H E pp 227–234 URL https://doi.org/10.56577/FFC-28.227
[50] Scott A R, Kaiser W R and Ayers Jr W B 1994 *AAPG Bulletin* **78**(8) 1186–1209 ISSN 0149-1423 URL https://doi.org/10.1306/A25FEAA9-171B-11D7-8645000102C1865D
[51] 2019 Ventilation Air Methane (VAM) Utilization Technologies Tech. Rep. EPA-430-F-19-023 United

States Environmental Protection Agency Washington, United States URL https://www.epa.gov/sites/default/files/2019-11/documents/vam_technologies.pdf
[52] Gao P F and Gou X L 2019 *ACS Omega* **4**(12) 14886–14894 URL https://doi.org/10.1021/acsomega.9b01573
[53] Maidukov G L 2015 *Coal of Ukraine* **10** 38–45
[54] Yashchenko I 2016 Status of coal mine methane degasification and utilization in Ukraine URL https://unece.org/fileadmin/DAM/energy/se/pp/coal/cmm/11cmm_gmi.cs_oct2016/5_Ukraine_GMI.pdf
[55] Bielousova K 2021 Shakhta "Stepova" skorotyla vykydy ta zaoshchadyla 6 mln kVt enerhii: yak tse vdalosia [Stepnaya mine reduced emissions and saved 6 million Kw of energy: How it was done] URL https://ecopolitic.com.ua/ua/news/shahta-stepova-skorotila-vikidi-ta-zaoshhadila-6-mln-kvt-energii-yak-ce-vdalosya/
[56] Singh A K and Sahu J N 2018 *International Journal of Green Energy* **15**(12) 732–743 URL https://doi.org/10.1080/15435075.2018.1529572
[57] Borowski M, Życzkowski P, Cheng J, Łuczak R and Zwolińska K 2020 *Energies* **13**(17) 4429 URL https://doi.org/10.3390/en13174429
[58] Ganushevych K, Sai K and Korotkova A 2014 Creation of gas hydrates from mine methane *Progressive Technologies of Coal, Coalbed Methane, and Ores Mining* ed Bondarenko V, Kovalevs'ka I and Ganushevych K (London: CRC Press) pp 505–509 ISBN 9780429226946 URL London
[59] Svietkina O, Kovalevska I, Sai K and Prokopenko K 2021 *E3S Web of Conferences* **230** 01004 URL https://doi.org/10.1051/e3sconf/202123001004
[60] Pedchenko L, Nyemchenko K, Pedchenko N and Pedchenko M 2018 *Mining of Mineral Deposits* **12**(2) 122–131 URL https://doi.org/10.15407/mining12.02.122
[61] Mimachi H, Takeya S, Yoneyama A, Hyodo K, Takeda T, Gotoh Y and Murayama T 2014 *Chemical Engineering Science* **118** 208–213 ISSN 0009-2509 URL https://doi.org/10.1016/j.ces.2014.07.050
[62] Bondarenko V, Svietkina O, Sai K and Petlovanyi M 2020 *ARPN Journal of Engineering and Applied Sciences* **15**(22) 2688–2697 URL http://www.arpnjournals.org/jeas/research_papers/rp_2020/jeas_1120_8406.pdf
[63] Bondarenko V, Sai K, Ganushevych K and Ovchynnikov M 2015 The results of gas hydrates process research in porous media *New Developments in Mining Engineering: Theoretical and Practical Solutions of Mineral Resources Mining* ed Pivnyak G, Bondarenko V and Kovalevska I (London: CRC Press) pp 123–127 ISBN 9780429225758 URL https://doi.org/10.1201/b19901

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Parameters evaluation in the process of solid phase pulp sedimentation in technological units of beneficiation plants

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Abstract. The aim of the research is the analysis and modeling of the process of sedimentation of the solid phase of the pulp in the technological units of processing plants to assess the density of particles of crushed ore. The paper analyzes domestic and foreign experience; methods of mathematical modeling were used, as well as methods of mathematical statistics and probability theory for processing the results of experiments. Scientific novelty consists in developing and substantiating a method for estimating the density of crushed ore particles in the process of their sedimentation directly in the process units of beneficiation plants. Practical value consists in developing a methodology for determining the characteristics of the enriched raw materials, which make it possible to form the degree of grinding necessary for the full disclosure of mineral formations. It was proposed to use the density of ore particles as an indicator of changes in the quality characteristics of the ore received for beneficiation, which is determined on the basis of measurements of the attenuation of volumetric ultrasonic waves and Lamb waves propagating in the pulp and the wall of the technological sump that is in contact with it. These measurements must be synchronized with the results of measurements of the pulp level in the sump during its working operation. The proposed method makes it possible to dynamically correct the parameters of the model of a closed ore grinding cycle, depending on the quality characteristics of the feedstock, and thereby form the conditions for the full disclosure of inclusions of the useful component in the product entering the magnetic separation or flotation.

1. Introduction

In the world practice of extraction and processing of minerals, geological reserves of ore with a high content of a valuable component are constantly declining [1, 2]. In this regard, mining and metallurgical enterprises are faced with the problem of rational use of ore with a high content of useful minerals and the development of technologies that allow efficient processing of low-grade ores [3]. Many efforts are being made to rationally use poor ores to extend the life of developed deposits and achieve acceptable financial results, such as optimizing the cut-off grade of a useful component [4, 5], mining production schedule optimization [6, 7], improvement of technologies for enrichment of extracted raw materials [8, 9].

In mineral processing, grinding is used to reduce the particle size of the ore in order to expose the valuable mineral component and recover it in subsequent processing operations such as flotation or magnetic separation [10]. The specific particle size of the crushed ore is the most important production indicator, which is a prerequisite for ensuring the quality of the resulting concentrate. The difficulty of achieving this condition is due to the fact that the process of grinding ore depends on a large number of operating parameters. In addition, the composition of iron ore is unstable and its quality deteriorates with a decrease in geological reserves [1].

Because of these difficulties, much attention has been paid to research into the grinding process [11]. With the development of new intelligent modeling and control methods, many of them have been successfully implemented in the field of mineral processing. Recently, advanced methods based on predictive control with a model have been widely discussed [12,13], supervisory control with intelligent decision support system [14, 15] and others to optimize the technological operations of ore beneficiation.

However, the grinding process is difficult to describe using mathematical models, since the real technological complex that implements it is a multiple input multiple output (MIMO) system with large inertia, nonlinearities, strong feedbacks, uncertainty, and the presence of a large number of perturbing factors [16]. Moreover, due to the lack of high-quality information support, which makes it possible to obtain real-time data on the main variables of the grinding process, its optimal control cannot be realized even on the basis of the most advanced models [17].

Under these conditions, the combination of the advantages of various methods of analysis and modeling makes it possible to more accurately and comprehensively simulate the real operating conditions of technological units [18, 19].

As the importance of process information grows [20, 21], there is a growing need to develop methods that can automate the processing and interpretation of the received data.

In work [22] the importance of data quality assessment for the development of semi-rigorous and empirical models of the primary grinding scheme at the concentrator is emphasized.

The key task of information support for the effective management of ore grinding-classification processes is the operational measurement of its granulometric composition and determination of the degree of grinding required, depending on the physical-mechanical and chemical-mineralogical properties of the enriched raw material. A promising direction in the development of methods to solve this problem is the use of non-contact non-destructive testing tools based on ultrasonic, magnetometric and nuclear-physical measurements [23].

There are different mineralogical varieties of ore that enters the beneficiation process. These varieties differ in several characteristics of inclusions of a useful component (fineness of inclusions), which requires various degrees of grinding for its complete disclosure. As a marker of the changed qualitative composition of the crushed ore, it is proposed to use the density of particles of the solid phase of the pulp in the process of its deposition directly in the technological units of concentrating plants. This parameter is determined based on the results of measuring the attenuation of bulk ultrasonic waves and Lamb waves propagating in the iron ore pulp and metal platinum that is in contact with it, as well as the level of the pulp in the process tank in which it is located.

2. Results

In many technological units of the processing plant, during their operation, particles of crushed ore are deposited in the pulp, i.e. in certain volumes, sedimentation and thickening of the solid phase of the pulp occurs. When performing operations such as desliming, thickening and clarification, these processes are part of the technology used, while in intermediate process tanks, sumps, they are a factor that introduces a disturbing effect, the effect of which on the technological process, in this regard, should be taken into account.

On figure 1 it is shown a typical technological scheme of the process of grinding ore during its enrichment, which is widely used in processing plants [22]. Initial ore and water are supplied to the mill, which operates in a closed cycle with hydrocyclones. Their flow is monitored by WT, FT sensors and controlled by closed local automatic control systems (ACS) based on proportional-integral-derivative (PID) controllers. The ore crushed in the mill is pumped through the Mill Discharge Sump to the Cyclone Clusters. Hydrocyclone sands are returned to the mill, and the overflow through the Rougher Feed Tank is fed further to flotation or magnetic separation. The diagram provides for the control of the mill rotation speed and the control loops for the additional water flow to the process sump and the performance of the pump supplying the pulp to the hydrocyclones. The control strategy and its technical implementation by the grinding cycle can differ significantly at different concentrators,

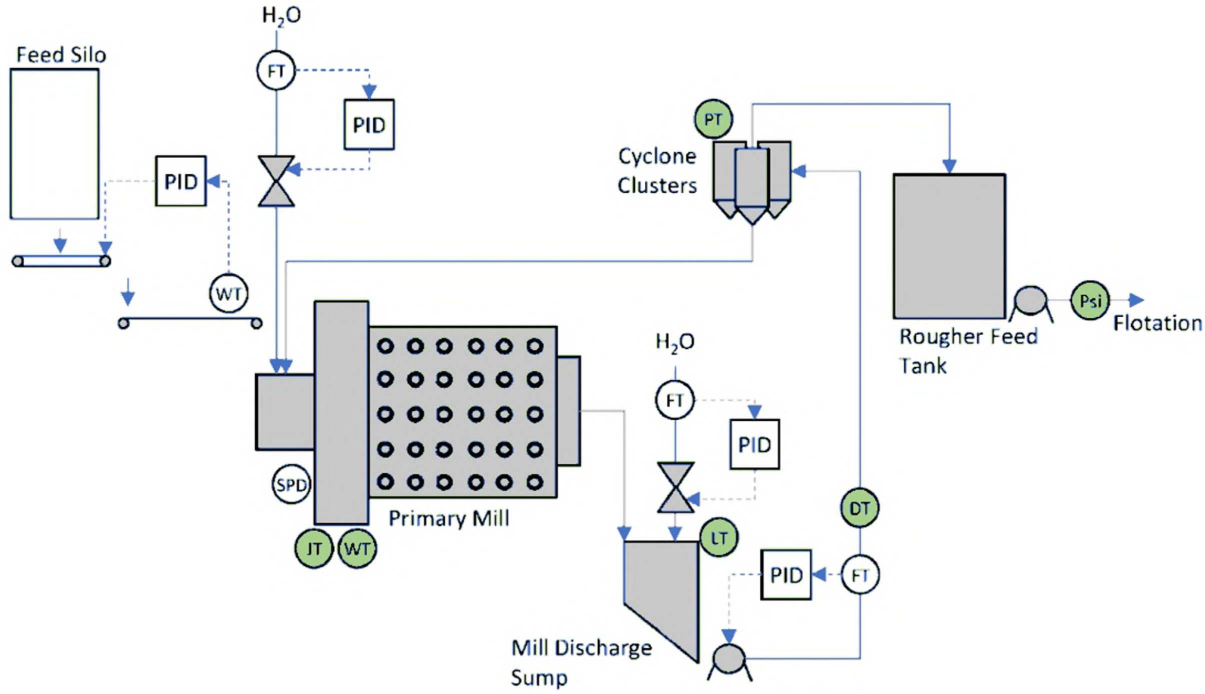

Figure 1. Technological scheme of the closed cycle of ore grinding [22].

As shown above, the task of the ore grinding cycle is the complete disclosure of inclusions of a useful mineral in the original ore for its subsequent extraction in concentrators. It follows from the above diagram that the characteristics of the product entering the hydrocyclones have a decisive influence on the conditions for its classification by size and specific gravity (density) of ore particles, and, consequently, on the results of extracting the useful component in the enrichment apparatus. Thus, the conditions and characteristics of the process of sedimentation of the solid phase of the pulp in the Mill Discharge Sump (taking into account the characteristics and conditions of the formation of input and output products, as well as additional water consumption) directly affect the quality indicators of the entire ore grinding cycle.

In accordance with the main position of the kinematic theory of sedimentation [24, 25] the relative velocity v_r of particles of the solid phase and liquid depends only on their local concentration. In this case, the flux density function is determined by the expression:

$$h(u) = u(1-u)v_r(u), \tag{1}$$

where u is the dimensionless volume fraction of solid particles.

For calculations of the designs of sedimentation tanks (thickeners) of continuous action, the transport term $q(t)u$ is used, where $q(t)$ is the controlled flow rate of the mixture [26, 27]. This leads to the equation of continuous suspension settling:

$$\frac{\partial u}{\partial t} + \frac{\partial\left(q(t)u + h(u)\right)}{\partial x} = 0, \tag{2}$$

where t is time and x is depth.

The function $h(u)$ depends on the material properties of the studied suspension [25, 28]. However, in order to use (2) to simulate continuous deposition, it is necessary to explicitly model the feed and discharge mechanisms and provide the boundary conditions [29].

On figure 2 it is shown the main notation and variables used in the mathematical model of the sump in the technological chain of the closed grinding cycle [22, 30, 31].

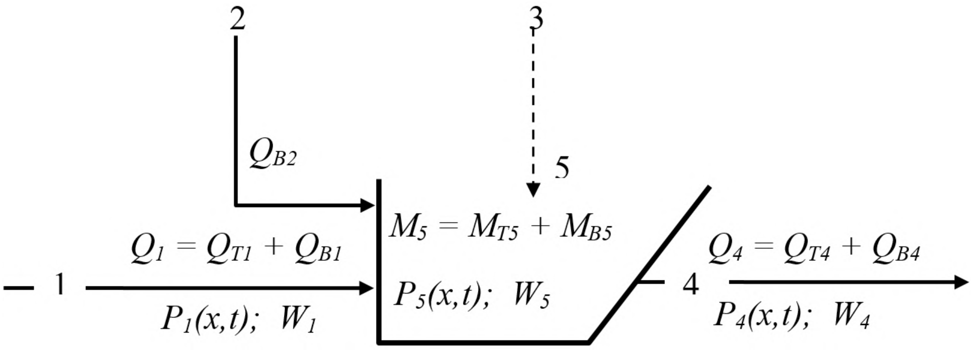

Figure 2. Balance of ore flows and granulometric composition of processed ore in the technological sump.

$Q(t)$ denotes the flows at the corresponding points of the technological process, W is the content of the solid phase of the pulp, $M(t)$ is the mass of material in the technological units at time t. In addition, when modeling the grinding cycle, the following designations were adopted: $P(x,t)$ is the cumulative yield of solid particles whose size is less than x; $\bar{X}_i = \left[\frac{\partial P(x,t)}{\partial x}\right]_i \Delta x$ – fraction of the crushed material, the particle size of which belongs to the size interval i. Consider the movement of crushed material through the technological sump. We will assume:

$$W_5 = \frac{M_{T_5}}{M_5} = \frac{Q_4}{Q_4} = W_4. \tag{3}$$

Material mass balance equations in the technological sump [22, 30]:

$$\bar{M}_5 = Q_{B_2}(t) + Q_1(t) - Q_4(t); \tag{4}$$

$$\bar{M}_{T_5} = Q_{B}1(t) - Q_4(t); \tag{5}$$

$$\bar{M}_{B_5} = Q_{B_1}(t) + Q_{B_2}(t) - Q_{B_4}(t); \tag{6}$$

$$M_5 = M_{T_5} + M_{B_5}; \tag{7}$$

$$Q_4 = Q_4 + Q_4. \tag{8}$$

Equation for the balance of mass and fineness of the crushed material for the technological sump:

$$\frac{\partial\left[P_5(x,t)M_5(t)\right]}{\partial t} = P_1(x,t)Q_1(t) - P_4(x,t), \tag{9}$$

or in discrete form:

$$\begin{array}{c}\bar{X}_5 = \left[-\frac{Q_{T_1}}{M_{T_5}} I\right] X_5 + \frac{Q_{T_1}}{M_{T_5}} X_1 \\ X_4 = X_5.\end{array} \qquad (10)$$

In this expression, X_1, X_5 and X_4 characterize the dynamics of the granulometric composition of the loaded, internal and output products of the technological sump [30].

System (10) can be written in the following form:

$$\begin{array}{c}\bar{X}_5 = A_5 X_5 - A_5 X_1 \\ X_4 = X_5.\end{array} \qquad (11)$$

where $A_5 = -\frac{Q_{T_1}}{M_{T_5}} I$.

In steady state:

$$\bar{X}_5 = \bar{M}_5 = 0; \qquad (12)$$

$$X_5 = X_1. \qquad (13)$$

Taking into account the fact that the output flow of the sump Q_4 is determined by the performance of the hydrocyclone feed pump, we can write:

$$\bar{M}_{T_5} = Q_{T_1} - Q_4 \frac{M_{T_5}}{M_{T_5} + M_{B_5}}; \qquad (14)$$

$$\bar{M}_{B_5} = Q_{B_2} + Q_{B_1} - Q_4 \frac{M_{B_2}}{M_{B_5} + M_{T_5}}. \qquad (15)$$

In the table 1 it is shown the density and grindability for 7 types of ores, which are mined and processed from one of the deposits of the Krivoy Rog iron ore basin. In this case, the following designations of ore types are accepted [32]: 1 – magnetite hornfelses; 2 – silicate-carbonate-magnetite hornfelses; 3 – red-banded magnetite; 4 – semi-oxidized and oxidized hornfelses; 5 – silicate schists, barren hornfelses, and quartz; 6 – magnetite-silicate-carbonate (poor) hornfelses; 7 – hematite-magnetite hornfelses.

Table 1. The results of the analysis of ores of various types.

Ore type	Quartz, %	Magnetite, %	Martit, %	Hematite, %	Siderite, %	Density, kg/m^3	Grindability, K
1	63.7	30.9	0	1.4	3.8	3431	1.06
2	68.4	21.7	0	0.4	9.1	3248	1.25
3	64.5	30.2	0	1.5	3.8	3414	1.48
4	65.4	24.4	3.3	3.7	3.2	3412	1.76
5	74.6	4.5	0	0.7	20.2	2989	1.29
6	75.2	6.8	0	0.8	17.2	3009	1.64
7	60.8	31.4	0	5.4	2.5	3530	1.18

The density of a particular type of ore with known values of the mass fraction of minerals is calculated by the formula [32]:

$$\rho = \frac{\rho \rho \beta}{\rho \alpha + \rho \left(\beta - \alpha\right)}, \qquad (16)$$

where ρ_m, ρ_n – mineral and rock density; β_m, α – mass fraction of the component in the mineral and ore; V_m, V_p – the volume of the mineral and rock in the ore.

Variations in the qualitative properties of enriched raw materials lead to changes in the results of grinding, opening of mineral formations and precipitation conditions (function $h(u)$) in the expression 2 particles of crushed ore in the technological sump.

The basic level of modern automatic process control systems (APCS) for grinding are local automatic control systems (ACS) of individual process variables (figure 1). At the same time, the models of regulated objects are approximated by an aperiodic link of the first order with sufficient accuracy for practical problems. Variations of the mineralogical varieties and characteristics of the ore received for enrichment lead to ambiguous results of the operation of the mill, technological sump and hydrocyclones, as well as their models, as objects of automatic control [32]. On figure 3 it is shown the results of the influence of this ambiguity based on the analysis of expressions (10), (14), (15).

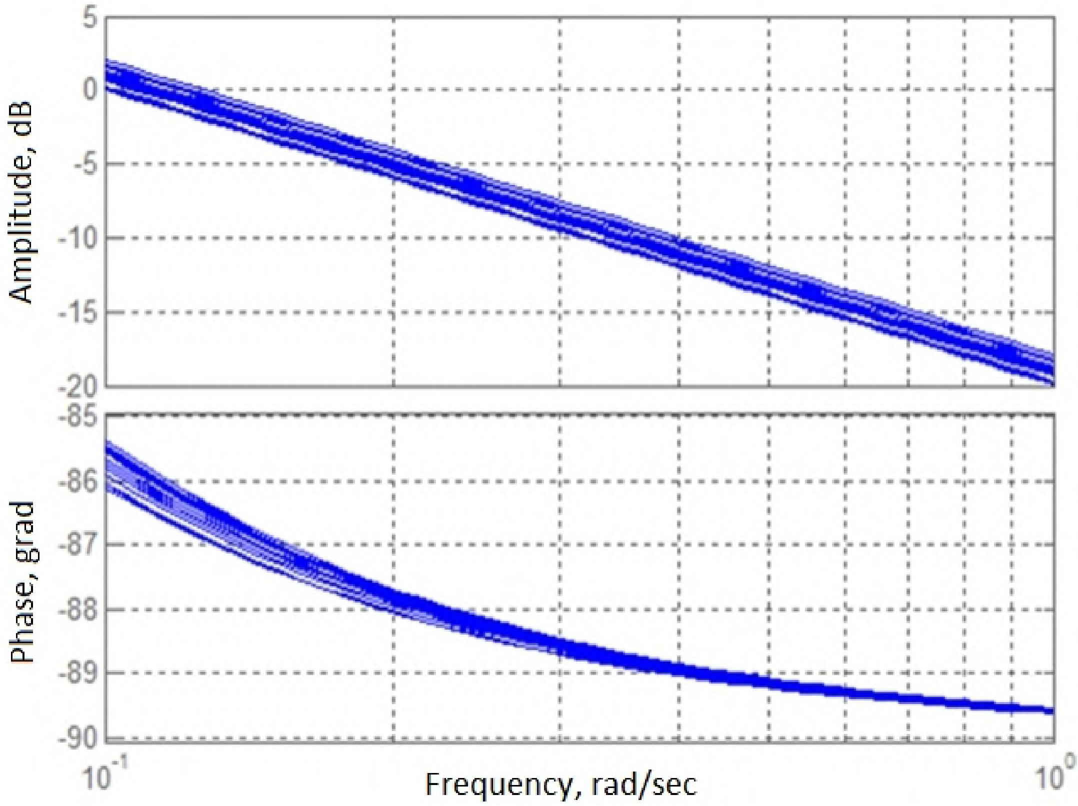

Figure 3. The family of frequency characteristics of the object of treatment with variation of parameters in the model.

To maintain the degree of grinding of the initial ore necessary for the full disclosure of the useful component, when $h(u)$ changes, the amount of additional water supplied to the technological sump is corrected.

It is proposed to estimate the changes in $h(u)$ based on the results of determining the density of particles of the solid phase of the pulp during its working settling in technological sumps of the grinding cycle.

Consider the process of movement of the pulp in the technological sump (figure 4).

The Bernoulli equation for the flow of a viscous liquid (pulp) has the form:

$$\rho g Z_1 + P_1 + \alpha_1 \rho \frac{V_1^2}{2} = \rho g Z_2 + P_2 + \alpha_2 \rho \frac{V_2^2}{2} + \rho g \sum h_n, \tag{17}$$

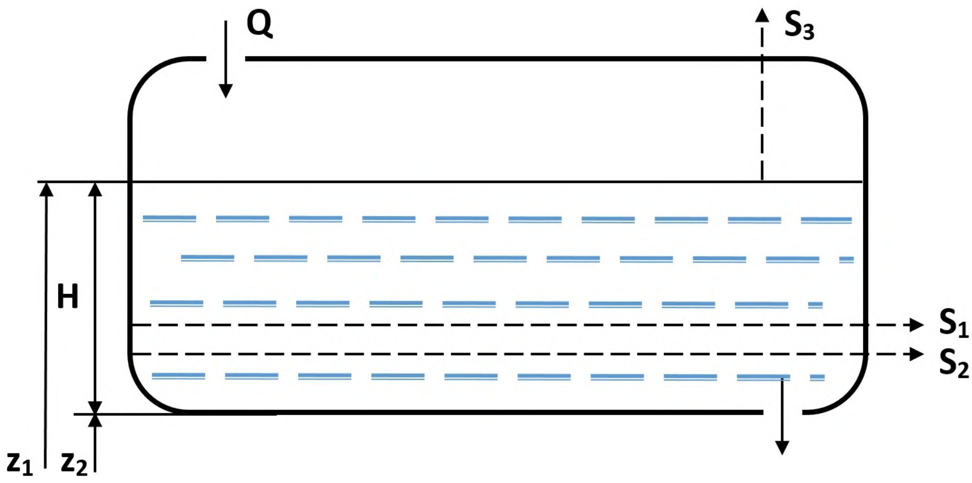

Figure 4. Scheme of measurements and movement of the pulp in the technological sump.

where ρ – pulp density.

Let the conditions:

$$P_1 = P_2, V_1 = 0. \tag{18}$$

In this case, expression 17 will take the form:

$$\rho g(Z_1 - Z_2) = \alpha_2 \rho \frac{V_2^2}{2} + (\sum h_n) g\rho; \tag{19}$$

$$\sum h_n = \xi_. \frac{V_2^2}{2g} + \xi_c \frac{V_2^2}{2g}, \tag{20}$$

where $\xi_{TP} = \xi_{TP}(W, \rho_T, \eta)$; $\eta_c = const$; η – controlled size class of crushed material in the pulp flow; $H = Z_1 - Z_2$; W – volume fraction of the solid phase of the pulp; ρ_T is the density of particles of the solid phase of the pulp.

Then:

$$H = (\alpha_2 + \xi_c + \xi_.) \frac{V_2^2}{2g}. \tag{21}$$

Let us denote by Q the volume of incoming pulp per unit time. From the condition of equality of the volumes of incoming and outgoing pulp for the velocity V_2, the relation:

$$V_2 = \frac{Q}{\sqrt{\alpha_2} S_{c2}}. \tag{22}$$

Taking into account (21), we have:

$$H = (\alpha_2 + \xi_C + \xi_{TP}) \frac{Q^2}{\alpha_2 S_{c2}^2} = (1 + \frac{\xi_c}{\alpha_2}) \frac{Q^2}{S_{c2}^2} + \xi_{TP}(W, \rho_T, \eta) \frac{Q^2}{\alpha_2 S_{c2}^2}. \tag{23}$$

Let the distance from the top edge of the sump to the pulp surface be determined by the signal S_3, which is a linear function of H, i.e.:

$$S_3 = A + BH, \tag{24}$$

where A and B are constants.

Then, taking into account expression 23, S_3 can be represented as:

$$S_3 = A' + \xi_{TP}(W, \rho_T, \eta)B', \tag{25}$$

where $A' = A + (1 + \frac{\xi_C}{\alpha_2})\frac{Q^2}{S_{c2}^2}$; $B' = B\frac{Q^2}{\alpha_2 S_{c2}^2}$.

Thus, the signal S_3 is a function of three variables W,ρ_T,η.

In accordance with the scheme shown in figure 4 according to the method described in the works [33], two more signals can be formed: S_2 – based on measurements of the attenuation of Lamb waves propagating in the wall of the technological sump in contact with the pulp and S_1 – based on measurements of the amplitude of high-frequency volumetric ultrasonic waves that have traveled a fixed distance in the pulp. Thus, the following system of functional dependencies can be formed:

$$\begin{gathered} S_3 = A' + \xi_{tr}(W, \rho T, \eta)B' \\ S_2 = W(\rho_T - \rho_V)C \\ S_1 = W_f(\eta). \end{gathered} \tag{26}$$

Let's pretend that ξ_{TP} – friction loss coefficient, directly proportional to pulp viscosity, i.e.:

$$\xi_{TP} = \lambda\frac{l}{d} = [(1 - W)\eta_B + W\phi(\rho_T, \eta)]\, D = D + WD\,[\phi(\rho_T, \eta) - \eta_B]\,, \tag{27}$$

where D is a constant value; η_B is the viscosity of water.

In this case:

$$S_3 = (A' + DB') + W(DB')[\phi(\rho_T, \eta) - \eta_B]. \tag{28}$$

If $W = 0$, then the pure water signal is equal to:

$$S_3^o = A' + DB'; \tag{29}$$

$$\tilde{S}_3 = S_3 - S_3^o = W\,[\phi(\rho_T, \eta) - \eta_B]\,A_2, \tag{30}$$

where $A_2 = DB'$.

Let's find the signal ratio $\tilde{S}_3$ and S_2 as well as S_1 and S_2:

$$\begin{gathered} S_{32} = \frac{\tilde{S}_3}{S_2} = \frac{[\phi(\rho_T,\eta)-\eta_B]A_2}{(\rho_T-\rho_B)c} = \frac{[\phi(\rho_T,\eta)-\eta_B]}{(\rho_T-\rho_B)}A_3 \\ S_{23} = \frac{S_1}{S_2} = \frac{f(\eta)}{(\rho_T-\rho_B)}\frac{1}{C}. \end{gathered} \tag{31}$$

The resulting expressions relate the content of the control size class of the crushed material with the density of the solid phase of the pulp. Thus, measuring the value, in accordance with the methodology described in the works [33], and the magnitude of the signal. S_3, you can determine the value t.

In connection with the fundamental importance for solving the problem of controlling the parameters of the fineness of the processed raw materials [34], supplied for enrichment, on the basis of the results obtained, the procedure for correcting the flow rate of additional water supplied to the process sump and the effect of this control action on the content of class -74 μm in the hydrocyclone discharge was modeled. On figure 5 it is shown the results of modeling the mass balance and dynamics of the granulometric composition of the processed ore in a closed grinding cycle. The root-mean-square discrepancy between the model and experiment was 0.92%.

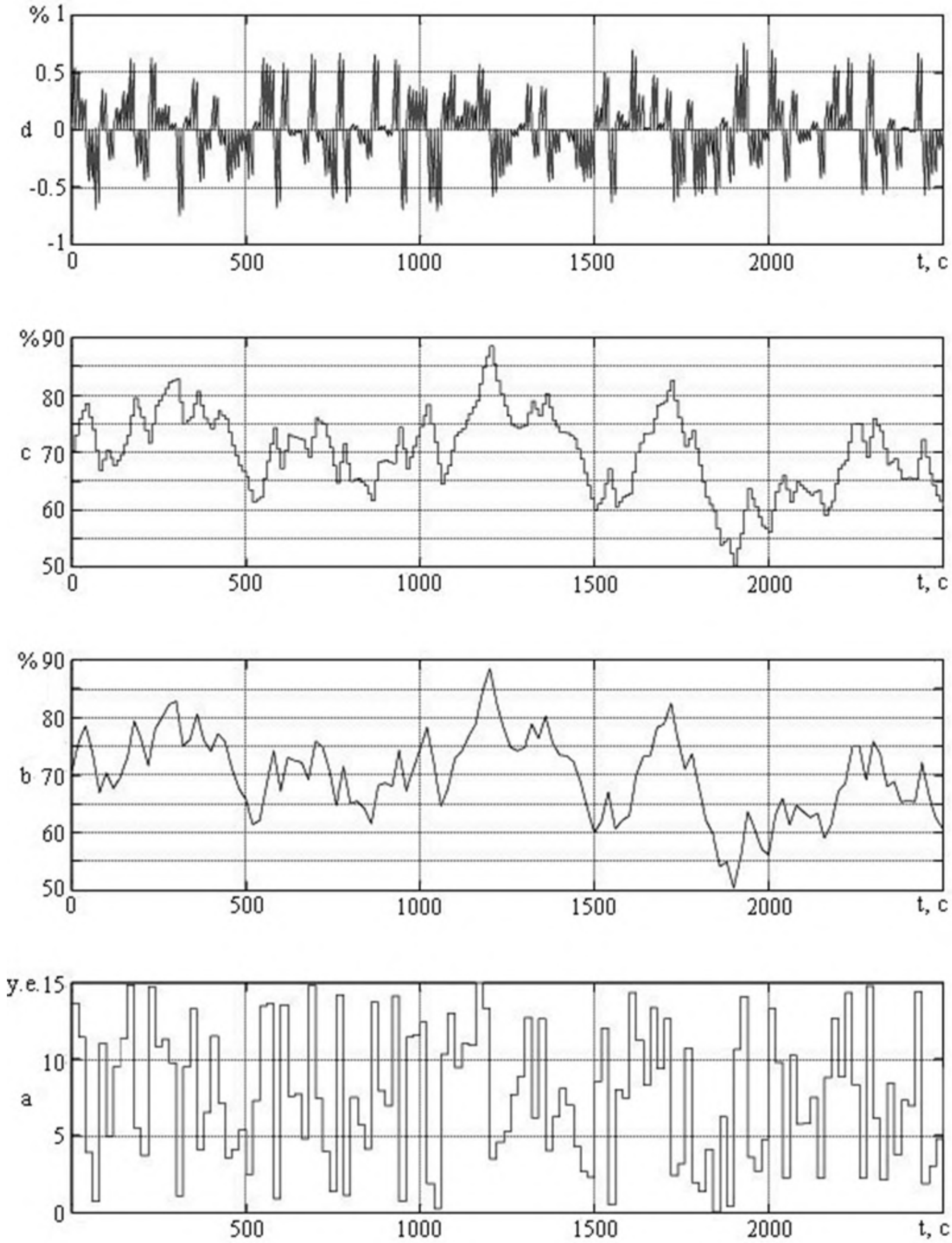

Figure 5. The results of modeling the mass balance and dynamics of the granulometric composition of the processed ore in a closed grinding cycle: *a* – input signal (consumption of additional water in the technological sump, c.u.); *b* – object output (class content -74 μm in the hydrocyclone drain, %); *c* is the output of the model (the content of the -74 μm class in the hydrocyclone drain, %); *d* – error signal, %.

3. Conclusions and further research

Under the conditions of the changing quality of the initial ore and the state of the technological equipment, in order to ensure the optimal operation of the subsequent technological stage - magnetic separation or flotation, the mathematical model of a closed grinding cycle, including a mill, a sump and a hydrocyclone, must contain a circuit that corrects its parameters depending on current physical-mechanical and chemical-mineralogical characteristics of processed raw materials.

It is proposed to use the density of its particles as an indicator of changes in the quality characteristics of the ore received for beneficiation, which is determined on the basis of measurements of the attenuation of volumetric ultrasonic waves and Lamb waves propagating in the pulp and the wall of the technological sump that is in contact with it. These measurements must be synchronized with the results of measurements of the pulp level in the sump during its working operation.

The proposed method makes it possible to dynamically correct the parameters of the model of a closed ore grinding cycle, depending on the quality characteristics of the feedstock, and thereby form the conditions for the full disclosure of inclusions of the useful component in the product entering the magnetic separation or flotation. The root-mean-square discrepancy between the model and experiment was 0.92%.

The direction of further research should be the approbation of the proposed approach in relation to spiral classifiers and concentrators.

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References

[1] Sotoudeh F, Nehring M, Kizil M, Knights P and Mousavi A 2020 *Resources Policy* **68** 101809 ISSN 0301-4207 URL https://doi.org/10.1016/j.resourpol.2020.101809
[2] Tishchenko S, Eremenko G, Kukharenko O, Pikilnyak A and Gaponenko I 2015 *Metallurgical and Mining Industry* **7**(8) 564–567 URL https://www.metaljournal.com.ua/assets/Journal/english-edition/MMI_2015_8/090Tishchenko.pdf
[3] Chen L, Gu Q, Wang R, Feng Z and Zhang C 2022 *Sustainability* **14**(17) 10766 ISSN 2071-1050 URL https://doi.org/10.3390/su141710766
[4] Lu X, Krstić M, Chai T and Fu J 2021 *IEEE Transactions on Control Systems Technology* **29**(3) 961–971 URL https://doi.org/10.1109/TCST.2020.2982353
[5] Tron V, Haponenko A, Haponenko I and Paranyuk D 2020 *E3S Web of Conferences* **201** 01025 URL https://doi.org/10.1051/e3sconf/202020101025
[6] Prasojo T S, Yulianto A, Hindarto A, Parinussa B and Arifien A 2013 *Procedia Earth and Planetary Science* **6** 24–29 ISSN 1878-5220 International Conference on Earth Science and Technology Proceedings September 2012 URL https://doi.org/10.1016/j.proeps.2013.01.003
[7] Golik V, Morkun V, Morkun N and Gaponenko I 2018 *Mining of Mineral Deposits* **12**(3) 63–70 URL https://doi.org/10.15407/mining12.03.063
[8] Van Tonder E, Deglon D A and Napier-Munn T J 2010 *Minerals Engineering* **23** 621–626 ISSN 0892-6875 URL https://doi.org/10.1016/j.mineng.2010.02.008
[9] Bicak O 2019 *Minerals Engineering* **142** 105927 ISSN 0892-6875 URL https://doi.org/10.1016/j.mineng.2019.105927

[10] Porkuian O, Morkun V, Morkun N and Serdyuk O 3919 *Acta Mechanica et Automatica* **13**(4) 262–270 URL https://doi.org/10.2478/ama-2019-0036
[11] Lv Z, Liu Y, Zhao J and Wang W 2015 *Applied Soft Computing* **27** 533–542 ISSN 1568-4946 URL https://doi.org/10.1016/j.asoc.2014.09.035
[12] Ramasamy M, Narayanan S S and Rao C D P 2005 *Journal of Process Control* **15**(3) 273–283 ISSN 0959-1524 URL https://doi.org/10.1016/j.jprocont.2004.06.006
[13] Kotov I, Suvorov O and Serdiuk O 2019 *Eastern-European Journal of Enterprise Technologies* **2**(4 (98)) 38–47 URL https://doi.org/10.15587/1729-4061.2019.155410
[14] Morkun V and Kotov I 2021 *E3S Web of Conferences* **280** 05002 URL https://doi.org/10.1051/e3sconf/202128005002
[15] Zhou P, Chai T and Sun J 2013 *IEEE Transactions on Control Systems Technology* **21**(1) 162–175 URL https://doi.org/10.1109/TCST.2012.2182996
[16] Zhao D and Chai T 2013 *Journal of Control Theory and Applications* **11**(3) 454–462 ISSN 1993-0623 URL https://doi.org/10.1007/s11768-013-1210-3
[17] Chai T, Ding J, Yu G and Wang H 2014 *IEEE Transactions on Automation Science and Engineering* **11**(4) 965–982 URL https://doi.org/10.1109/TASE.2014.2308576
[18] Cleary P W 2015 *Minerals Engineering* **73** 85–99 ISSN 0892-6875 Special issue: Comminution URL https://doi.org/10.1016/j.mineng.2014.09.005
[19] Liu B, Hao D, Gao X and Zhang D 2021 *Applied Sciences* **11**(13) 5835 ISSN 2076-3417 URL https://doi.org/10.3390/app11135835
[20] Ge Z, Song Z, Ding S X and Huang B 2017 *IEEE Access* **5** 20590–20616 URL https://doi.org/10.1109/ACCESS.2017.2756872
[21] McCoy J T and Auret L 2019 *Minerals Engineering* **132** 95–109 ISSN 0892-6875 URL https://doi.org/10.1016/j.mineng.2018.12.004
[22] Brooks K, le Roux D, Shardt Y A W and Steyn C 2021 *Minerals* **11**(9) 954 ISSN 2075-163X URL https://doi.org/10.3390/min11090954
[23] Porkuyan O V 2007 *Bulletin of the East Ukrainian National University* **4(110)** 171–176
[24] Kynch G J 1952 *Trans. Faraday Soc.* **48** 166–176 URL https://doi.org/10.1039/TF9524800166
[25] Bürger R and Wendland W L 2001 *Journal of Engineering Mathematics* **41**(2) 101–116 ISSN 1573-2703 URL https://doi.org/10.1023/A:1011934726111
[26] Hassett N J 1958 *The Industrial Chemist and Chemical Manufacturer* **34** 116–120
[27] Talmage W P and Fitch E B 1955 *Industrial & Engineering Chemistry* **47**(1) 38–41 URL https://doi.org/10.1021/ie50541a022
[28] Bustos M C, Concha F, Bürger R and Tory E M 1999 *Sedimentation and Thickening: Phenomenological Foundation and Mathematical Theory* (*Mathematical Modelling: Theory and Applications* vol 8) (Netherlands: Kluwer Academic Publishers) URL https://doi.org/10.1007/978-94-015-9327-4
[29] Bürger R, Concha F, Karlsen K and Narváez A 2006 *Mathematical and Computer Modelling* **44**(3) 255–275 ISSN 0895-7177 URL https://doi.org/10.1016/j.mcm.2005.11.008
[30] Ragot J, Roesch M, Degoul P and Berube Y 1976 *IFAC Proceedings Volumes* **9**(5) 129–142 ISSN 1474-6670 2nd IFAC Symposium on Automation in Mining, Mineral and Metal Processing, Johannesburg, S Africa, 13-17 September URL https://doi.org/10.1016/S1474-6670(17)67199-4
[31] Grinman I G and Blyakh G I 1967 *Control and regulation of the granulometric composition of grinding products* (Alma-Ata: Nauka)
[32] Koryakov-Savoysky B A, Gulenko T I and Lopatin V I 1971 *Automation of mining and metallurgical production* **7** 13–20
[33] Porkuyan O V 2004 *Development of ore deposits* **87** 70–75
[34] Mladetskyi I K and Kolesnyk M V 2007 *Naukovi pratsi DonNTU* **15(131)** 104–108

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Scientific and technical problems of transition from open pit to combined technologies for raw materials mining

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Scientific and technical problems of transition from open pit to combined technologies for raw materials mining

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Abstract. In Kryvyi Rih iron ore basin, long-term and intensive mining of deposits applying open pit methods have resulted in significant areas disturbed by open pits, dumps and tailings storage facilities. Hundreds of thousands of hectares of fertile arable land are already unsuitable for agriculture and sometimes for living. Thousands of tonnes of dust from dumps and tailing ponds deteriorate the surrounding nature every year and pollute the atmosphere in mining basins. Industrial ore breaking in open pits using bulk blasting causes emissions of a significant amount of harmful dust and carcinogenic substances. The environmental situation in open pit mining areas is often close to critical. In addition, bulk blasting forms a seismic wave, which in some cases destruct civil buildings and industrial facilities. The article proposes ways of gradual transition from mining mineral deposits by open pit methods to environmentally friendly technologies of open pit-underground and underground mining. It is established that such transition is a forced and at the same time choiceless way of developing mining areas, in particular Kryvyi Rih iron ore basin. The paper notes that the main problems of this transition include geomechanical stabilization of the rock massif during construction of underground mines in areas of possible impacts of open pit fields. The paper develops the fundamental study of the problems of controlling the stress-strain state of the massif during transition from the open pit to combined technology of deposit mining. Technologies of combined mining that involve formation of a transition belt with backfilling the worked-out space with compound mixtures are studied as well. It is proved that development of theoretical foundations for controlling the stress-strain state of the massif during transition from the open-pit to combined technology of deposit mining, study and design of technological solutions that contribute to transition to open pit-underground and underground mining, is an urgent scientific, technical and practical problem of great importance.

1. Introduction

In terms of explored iron ore reserves Ukraine ranks first-second among the most powerful mining countries. The main reserves of iron ores are located on the Ukrainian crystalline shield in Kryvyi Rih iron ore basin. This basin along with Kremenchuk and Bilozersk iron ore districts forms the region of Greater Kryvyi Rih, or Kryvyi Rih iron ore basin – Kryvbas.

Iron ores are represented mainly by three geological and industrial types: rich magnetite-hematite-martite ores, ferruginous quartzites and oolite brown iron ores [1].

Rich ores are used without processing.

Magnetite and cumingtonite-magnetite quartzites, brown iron ores of Kryvbas and brown iron ores of Kerch basin are processed by simple methods – washing and magnetic separation [2].

Oxidized quartzites and brown iron ores are difficult to process and require roasting-magnetic or gravitational-flotation processing methods [2].

The thickness of magnetite and oxidized ferruginous quartzites is up to 100–200 m, occasionally up to 500 m, the content of iron oxides in ore is from -15 to 46%, phosphorus – from -0.03 to 0.16%, sulfur – from -0.02 to 0.24% [3].

Of the total volume of iron ore raw materials (IORM) mined in Ukraine, Kryvbas accounts for about 80%, at that the share of the open pit mining method is about 70–80% [4].

Ferruginous quartzites are mined mainly by open pit and partly underground methods.

The dynamics of iron ore production by mining enterprises of Ukraine over the past ten years is shown in figure 1.

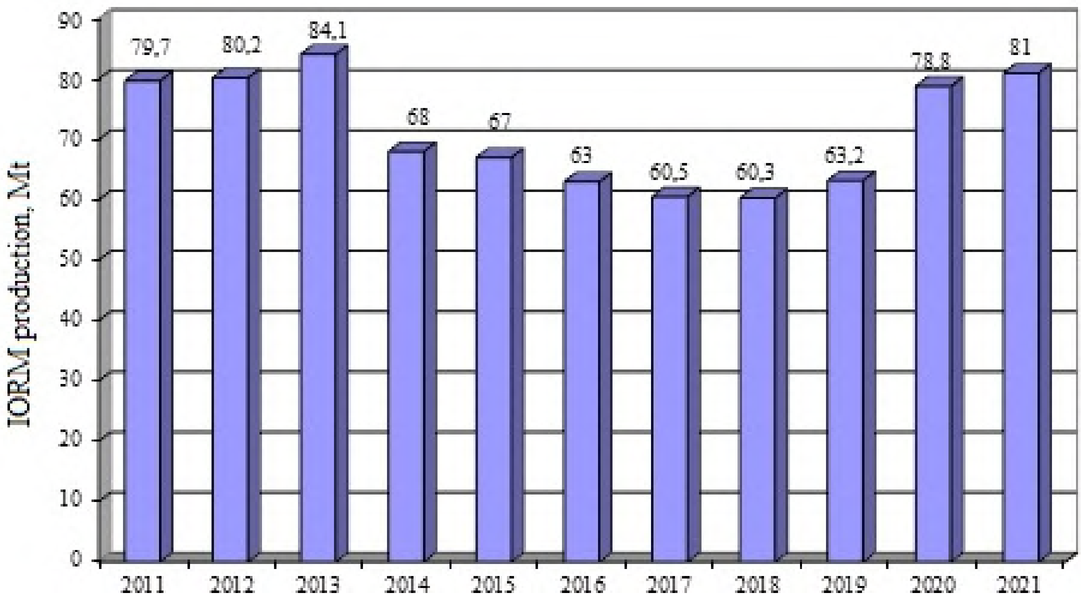

Figure 1. Dynamics of iron ore raw material production by mining enterprises of Ukraine in 2011–2021.

In the base year of 2013, mining enterprises of Ukraine produced 84110.4 kt of iron ore and concentrate. which is by 4.8% more than in 2012, including: non-sintered iron ore – 14242.2 kt (+6.0%); iron ore concentrate 69868.2 kt (+4.6%), of which 30431.5 kt (at the level of the previous year) of marketable concentrate; iron ore sinter of the PJSC "PivdGZK" – 2413.8 kt (+19.3%); iron ore pellets – 23965.3 kt (+9.1%); fluxing metallurgical limestone – 15437.5 kt (-7.1%), including 2109.5 kt (-19.7%) of the dolomitic one [1].

According to the U.S. Geological Survey, Mineral Commodity Summaries, January 2022, Ukraine mined 78.8 and 81.0 Mt of in 2020 – 2021 respectively [5].

In Kryvyi Rih basin, lean iron ores or magnetite quartzites are mined by open pit methods by the PrJSC "Inhulets GZK", the PrJSC "PivdGZK", the Mine Administration for open pit ore mining of the PJSC "ArcelorMittal Kryvyi Rih", the PrJSC "Central GZK" and the PrJSC PivnGZK".

The open pit method of mining causes alienation of much more land. In Kryvyi Rih basin, which accounts for up to 85% of marketable IORM production in Ukraine, mining has disturbed thousands of hectares of fertile arable land.

According to the State Enterprise "State Institute for Design of mining enterprises "Kryvbasproekt", in Kryvyi Rih basin land expenditure per unit of marketable products is 13 times larger when applying open pit mining methods than in underground mining. Air pollution by dust and gas emissions is also much greater as compared to underground works.

During open pit mining, the damage caused to the environment per 1 t of marketable products is 3.5 times greater than in underground mining, and considering the quality of marketable products it is 3 times larger [6].

The above-mentioned conditions of iron ore deposits operation and their impact on the environment deterioration when applying the open pit mining method are summarized (table 1).

Table 1. Conditions of iron ore deposits operation and the impact of production processes on the environment in open pit mining.

Deposit operation conditions	Production processes	Implications for the environment
Depth of ore deposits (up to 450 m)	Opening operations while stoping	The Earth's surface disturbance, soil quality deterioration, storage of significant overburden volumes in dumps, change in the hydrological conditions of the area
High strength of overburden and ores	Application of drilling and blasting	Large volumes of dust and gas emissions into the atmospheric air, seismic impact
Qualitative characteristics of ores (22–38% Fe)	Necessity of processing ore raw materials mined	Storage of processing wastes, creation of tailings storage facilities, harmful emissions into the air, use and pollution of significant amounts of water resources

Every 1 kt of rock mass mined by GZKs produces just about 200 t of iron ore products. At that, 40 m^2 of land is alienated and 50 m^2 of land is flooded, 110 m3 of highly mineralized waters is consumed, 2.5 t of fine dust and 1.8 t of poisonous gases are emitted into the atmosphere.

As compared to the open pit methods, underground mining of deposits demonstrates the following significant environmental advantages:

- reduction of area losses caused by formation of open pits and waste dumps;
- possible separate extraction of rich iron ores of different varieties;
- use of overburden rocks as raw materials for by-product production;
- lower losses of ore raw materials in the subsoil;
- possible creation of nature reserve areas, recreational areas after completion of the deposit operation.

Thus, one of the main ways to reduce the negative impact of open pit mining on the environment of the basin consists in gradual transition from the open pit mining of mineral deposits to environmentally friendly technologies of open pit-underground and underground mining. Such a transition is found to be a forced and at the same time choiceless way of developing mining areas, in particular Kryvyi Rih iron ore basin. The main problems of such transition will include those of geomechanical stabilization of the rock massif during construction of underground mines in areas of possible impact of open pit fields.

2. Purpose

The paper develops the fundamental study of the problems of controlling the stress-strain state (SSS) of the massif during transition from the open pit to combined technology of deposit mining. Technologies of combined mining that involve formation of a transition belt with backfilling the worked-out space with compound mixtures are studied as well.

So, the paper aims to develop theoretical foundations for controlling the stress-strain state of the massif during transition from the open-pit to combined technology of deposit mining, study and design technological solutions that contribute to transition to open pit-underground and underground mining.

3. Analysis of researches and publications

Deterioration of mining conditions (increased depth of mining, reduced thickness of ore deposits) with a simultaneous increase in energy consumption leads to reduction in parameters of working sites, an increase in angles of the working wall and conservation of a significant part of the open pit [1]. Deconservation of the open pit reserves after completion of every stage of mining results in a sharp increase in the volume of stripping, and given limited investments and a long period of their return, technical and economic indicators deteriorate significantly. The environmental problems of the open pit method of mining add to the already difficult condition of modern mining and processing plants (GZKs).

One of the directions of solving this theoretical and technical problem is the wider applicationt of combined mining with the integrated use of open pit-underground and underground methods of deposit mining.

Combined open pit-underground mining allows for maintaining the production capacity of mining enterprises for a long time. Along with that, introduction of scientific recommendations and technological solutions for combined mining of reserves has enabled a number of foreign companies that traditionally applied the open pit method to involve areas of deposits considered unpromising into intensive operation [7].

The sequence of application of open pit and underground mining methods is determined considering the required productivity of the enterprise and specifics of the deposit [8].

Depending on the location of underground mine and open pit fields within the deposit, three characteristic schemes can be distinguished [7]:

- with a combination of work in one vertical plane (underground mining operations (UMO) are carried out under the open pit);
- with a combination of works in the horizontal plane (UMO are carried out in the pit wall);
- with a partial combination in both the vertical and horizontal planes.

The Kidd Creek Mine in Ontario (Canada) is an example of a systematic transition from open pit to underground mining, [9].

Construction of the underground mine started when the depth of the open pit was actually 150 m (the design depth is 250 m), i.e. 7-10 years before completion of open pit mining operations (OPMO).

The Australian copper-gold deposit Osborne located in Queensland has been mined by underground methods in the pit wall since 1996. The pit was decommissioned the same year. The underground work site is opened out through an inclined adit with a portal at hor. 80 m of the depleted pit, and vertical shafts [10].

The Australian Northparkes deposit operated by a group of mines that conduct UMO not after completion of OPMO but simultaneously with them is of particular interest. The company produces high-quality copper-gold concentrate [11].

Considerable experience in the simultaneous conduct of open pit and underground operations has been accumulated at the largest copper-gold deposit Grasberg which was explored in 1988.

Grasberg is the largest gold mine and the third largest copper open pit, as well as the world's highest located open pit. It is located in the province of Central Papua, Indonesia [12].

The mine consists of an open pit and an underground mine. The pit provides high production at low cost. The underground mine operates the under-pit ore massif and several individual deposits near the pit.

Mines "Vihanti", "Hammaslahti", "Pyhäsalmi", "Luikonlahti" and "Kotalahti" (Finland) are mining a number of deposits of polymetallic ores by open pit, underground and combined open pit-underground methods. Pyhäsalmi Mine Oy is the deepest non-ferrous metal mine in Europe (1444 m deep).

The Pyhäsalmi mine operates a copper polymetallic deposit with the 3-4% copper content in the ore and also extracts lead, zinc, sulfur and rare earth elements. The upper part of the deposit is worked out by a pit to the depth of 120 m, the lower part – by the underground method, using room systems with backfilling, as well as a system of horizontal layers with consolidating backfill [11].

The Virtasalmi copper mine operates a polymetallic ore deposit and is being worked out by open pit and underground methods. To the depth of 175 m, the deposit was worked out by both open pit and underground methods with taking the rock mass from the underground part to the daylight surface along the ramp. With transition to underground mining, ventilation raises were created from the non-operating wall of the pit to air underground mining operations [13].

"Sherrit Gordon" (Canada) has transited from the open pit method to the underground one. The Ruttan mine operates the copper ore deposit by the open pit to the depth of 120-160 m. The orebody thickness is 36 m, its length is 820 m, the dip is 70 degrees. The explored reserves for UMO are 27 Mt of ore with the copper content of 1.74%. The development system is room mining with subsequent backfilling of the worked-out space with processing tailings [14].

The copper-cobalt deposit Kamoto in Katanga is also mined by the open pit-underground method. The steeply dipping part of the deposit directly under the pit is worked out by a room system with backfilling, and the flat part is worked out by a room-and-pillar method [15].

To the depth of 170 m the deposit was mined during 15 years, then 10 years later they started underground mining operations. The period of simultaneous OPMO and UMO made 8 years [16].

The Tishinske polymetallic deposit (Kazakhstan) is represented by two steeply dipping orebodies "Osnovne" and "Paralelne" with a dip of 80-85 degrees and the thickness of 10-70 m [17].

Initially, the deposit was supposed to be worked out in combination, by an open pit to the depth of 380 m and an underground mine with a 60 m high safety ore pillar left in the bottom of the pit, which is equal to the height of a level. At the underground mine, room systems are applied with the backfilling of the worked-out space and the use of self-propelled equipment.

The Gaiske copper-pyrite deposit is represented by a series of orebodies with the thickness of 35-40 m and over. It is mined by the combined open pit and underground method in one vertical plane [18].

Finsch deposit is another good example of combined mining. It was developed by the open pit method until the 1990s [19]. Since 1991, mining has been carried out by the underground method under the shell of the depleted open pit.

The Kiruna Mine is the world's largest and most modern mine with open pit-underground iron ore mining (figure 2). The mine is located in Kiruna, Sweden, and owned by the Swedish mining company Luossavaara-Kiirunavaara AB. In 2018, the mine produced 26.9 Mt of iron ore.

Until the 1960s, the mine applied the open pit ore mining method. Now iron ores are mined by the underground method [20].

Based on the analysis performed, it is established that the choice of combined mining technology is to a great extent impacted by the stress-strain state of the rock massif.

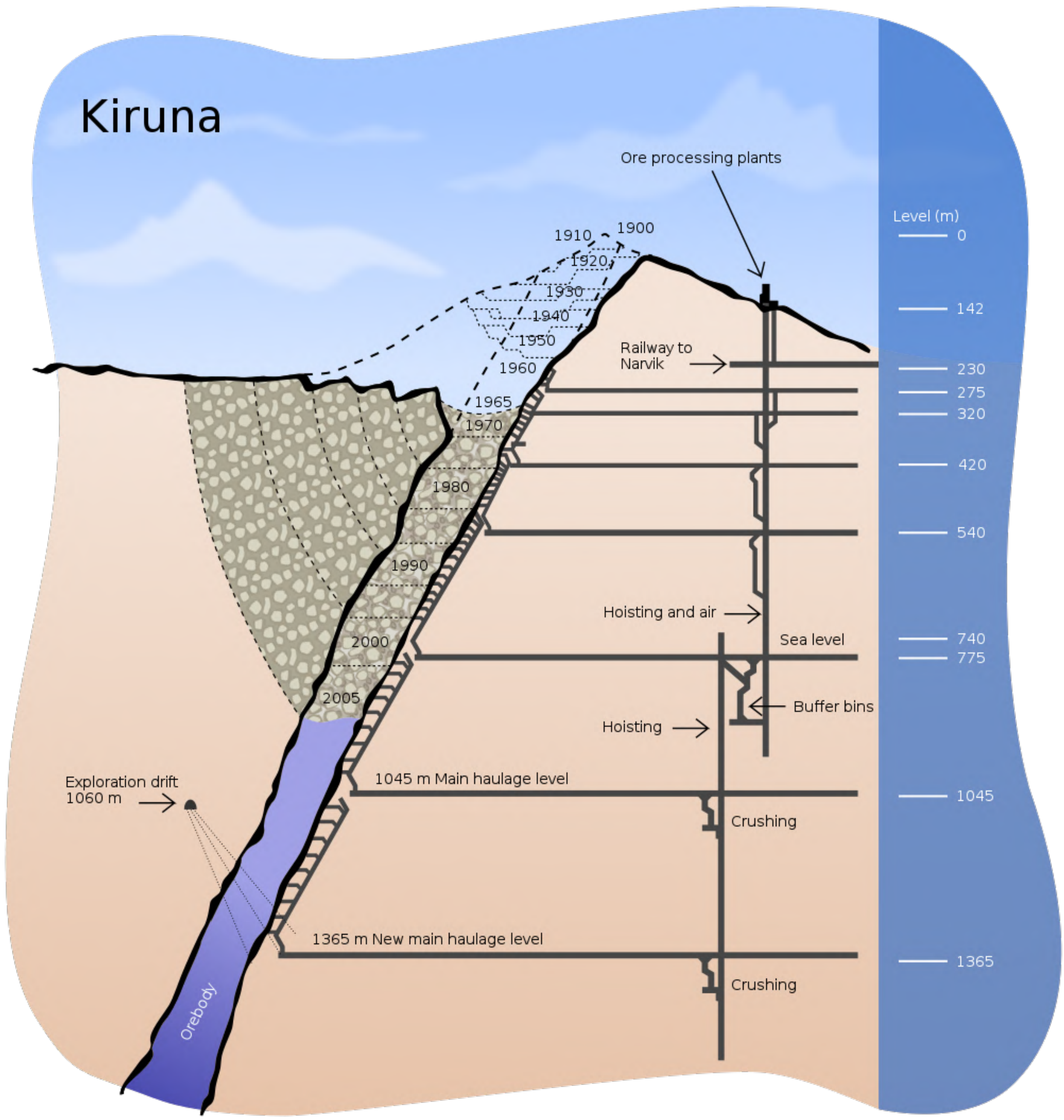

Figure 2. Kiruna mine of Luossavaara-Kiirunavaara AB.

Mathematical methods enable assessing current conditions and obtaining predicted data for enhancement and development of new mining methods, improvement of the flowsheet, selection of optimal parameters for stoping.

4. Methods

An important element of transition from technologies of open pit mining of magnetite quartzites to those of open pit-underground and underground mining is the control of rock landslides in areas of pit fields undermined by underground workings. Such areas may be potential sources of man-made disasters.

The stress-strain state of the massif is known to significantly depend on both natural and artificial conditions of the mining environment.

Among natural properties, geological heterogeneities, in particular the availability of structural, tectonic and other disturbances, are of special significance.

Among artificial disturbances of the rock massif, those occuring during the preparatory-development and especially stoping operations have the greatest impact [21]. In combined open pit-underground mining, the nature of the massif SSS change is impacted by both underground and open pit mining operations. Therefore, information about such disturbances is extremely necessary both at the design stage and in the process of deposit mining [22].

Consequently, a comprehensive assessment of values of current stresses in the massif, prediction of their nature and causes of their change during combined open pit-underground and underground stoping are necessary. This information will enable assessing current conditions and obtaining initial data for improvement of the applied and development of new combined flowsheets of open pit-underground mining, selecting optimal parameters for stoping operations and determining their rational sequence [23].

Consider application of mathematical methods on the example of the impact of the Pershotravnevyi open pit of the PrJSC "PivnGZK" on geomechanical properties of the rock massif at the bottom and in walls of the open pit.

Consider the geomechanical conditions for transition to underground operations during mining the reserves of the Pershotravneve deposit by the open pit-underground method. Minerals are mined by the H_k deep open pit with the angle of the walls ϕ_k. Underground mining operations are supposed to be carried out under the pit at the depth h from the daylight surface.

Assess the deposit area adjacent to the open pit on the basis of solving the plane problem of the theory of elasticity. The components of the stress fields are determined in stages. First, determine the amount of load removed from the pit bottom. It is a uniformly distributed load with an intensity $\gamma_p H_k$.

The values of the stress components can be written as

$$\sigma_{X_1} = \frac{\gamma_p H_k}{\pi}\left(arctg\frac{a_k - x_1}{z_1} + arctg\frac{a_k + x_1}{z_1}\right) + \frac{2a_k\gamma_p H_k z_1(x_1^2 - z_1^2 - a_k^2)}{\pi((x_1^2 + z_1^2 - a_k^2) + 4a_k^2 z_1^2)}, \tag{1}$$

$$\sigma_{Z_1} = \frac{\gamma_p H_k}{\pi}\left(arctg\frac{a_k - x_1}{z_1} + arctg\frac{a_k + x_1}{z_1}\right) - \frac{2a\gamma_p H_k z_1(x_1^2 - z_1^2 - a_k^2)}{\pi((x_1^2 + z_1^2 - a_k^2) + 4a_k^2 z_1^2)}, \tag{2}$$

$$\tau_{X_1 Z_1} = \frac{4a_k\gamma_p H_k x_1 z_1^2}{\pi((x_1^2 + z_1^2 - a_k^2) + 4a_k^2 z_1^2}, \tag{3}$$

where a_k is half the width of the pit bottom; γ_p is the volumetric weight of ore in the massif; x_1, z_1 are the coordinates along the corresponding axes.

Analysis of the results obtained shows that the value of the horizontal component grows with an increase in the pit bottom depth and width. The value of the vertical component increases only with an increase in the width of the pit bottom, and the change in the pit depth does not impact the value of this parameter.

The values of the lateral earth pressure coefficient λ_f are also maximum in the area that is directly adjacent to the contour of the open pit and decreases as the depth and width of the pit bottom increase [24].

In this paper, SolidWorks 2015 software is used to determine the SSS of a rock massif related to the determination of the stress field [25].

Table 2 presents initial physical and mechanical properties of rocks and the backfill material for calculating stresses and strains applying SolidWorks 2015.

Table 2. Physical and mechanical properties of rocks and backfill material.

Parameters	Magnetite quartzites, waste rock	Backfill
Young's modulus, MPa	15000–60000	500
Volumetric weight, kg/m^3	3400	2000
Tensile strength, MPa	6–18	0,5–1,0
Compression strength, MPa	60–180	5–10
Poisson's ratio	0.25	0.15

To calculate the stress-strain state of the combined massif, options of the classical scheme of open pit-underground mining of magnetite quartzites are accepted for the average statistical conditions of transition from open pit to underground mining.

The current average depth of open pits at the level of 350 m is accepted as the final pit depth (or the boundary of transition from open pit to underground mining).

The second stage of the deposit opening during transition from the open pit to underground mining method is carried out by a vertical shaft located outside the open pit in the footwall of the deposit.

The scheme of this kind is expedient for opening at the deposit depths of over 800 – 1000 m, which is characteristic of all Kryvbas deposits. In addition, Kryvbas mining enterprises have accumulated a huge experience of applying this particular scheme for underground opening of deposits.

With less than 800 m depths of deposits, or in case of no funds for construction of mine shafts and absence of prospects for long-term mining by the open pit-underground or underground method, other opening schemes are applied.

Creation of ramps or spiral ramps from technological platforms in the open pit is the main scheme. It is expedient if self-propelled drilling, loading, and transport equipment is used. But in case of low costs of magnetite quartzites, such a scheme may not always be economically viable.

A grid of finite elements of the initial design model is given in figure 3. The model is adequate in size to the site where the technology under study is applied and is used to calculate stresses during open pit-underground mining.

Below are given the results of calculating stress fields in the rock massif when stoping under the open pit bottom, as well as when backfilling stopes with consolidating backfill mixtures.

Isolines of the main stress field around the rooms with an open stoping space and rooms backfilled with a consolidating mixture and collapsed waste rocks are presented in figure 4.

To visually determine the stresses, all isolines have a certain stress value in Pa and correspond to a certain color scale.

All the options proposed by the authors have the following general characteristics.

The vertical shaft of the mine is located in the footwall of the deposit. The height of the underground level is 90 m.

The main crosscuts, drifts of the foot- and hanging walls are driven from the shaft to the orebody at levels –440 m and –530 m.

The level-room system is used for stoping.

Three fundamental schemes of work development are investigated.

The idea behind the first flowsheet of transition from the open pit to underground method of mining an ore deposit is illustrated in figure 4.

After the complete drawing of the broken ore, the stoping space of the worked-out room is filled with waste rocks resulted from driving underground and open workings.

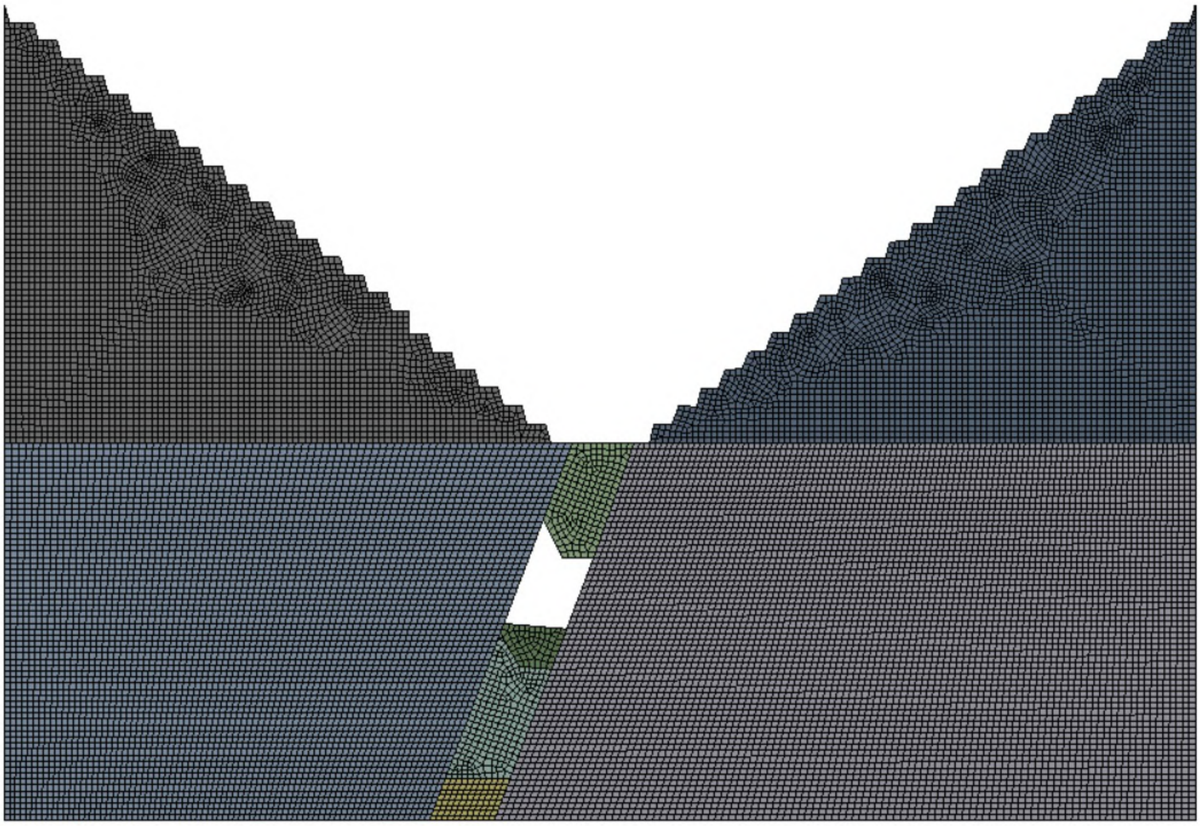

Figure 3. Grid of finite elements of the initial design model adequate in size to the site where the technology under study is applied to mine magnetite quartzites.

The calculated isolines of the main stresses σ_1 of the rock massif when applying open pit-underground mining of the magnetite quartzites deposit with ore breaking and drawing and subsequent backfilling the stoping space of the worked-out room with waste rocks are presented in figure 4.

As is seen in figure 4, the general picture of the distribution of the field of stresses is classic: the greatest absolute magnitude of stress occurs near the angles of the formed stope from the side of the ore massif. Small concentration of stresses is observed in the corners on the bottom of the room.

Significant maximum stresses σ_1 in the corners of the room appear due to the action of compressive stresses. The stresses σ_1 decrease depthward into the ore massif, and their distribution becomes more uniform.

Concentration of maximum stresses σ_1 is observed in the upper and lower corners of the rooms that are not backfilled, and only in the lower part of the backfilled ones.

In some cases, lateral exsposures of the unfilled stope may be distinguished by the fact that tensile stresses σ_3 appear in the central part of the lateral generatrix. In this case stresses σ_1 are reduced from the boundary of the room depthward into the ore massif.

5. Results

Today, development of deposits of ferruginous quartzites of Kryvbas by underground mining has equaled the cost of open pit operations. At the same time, the cost of open pit operations will steadily increase, but in underground mining it will remain rather stable.

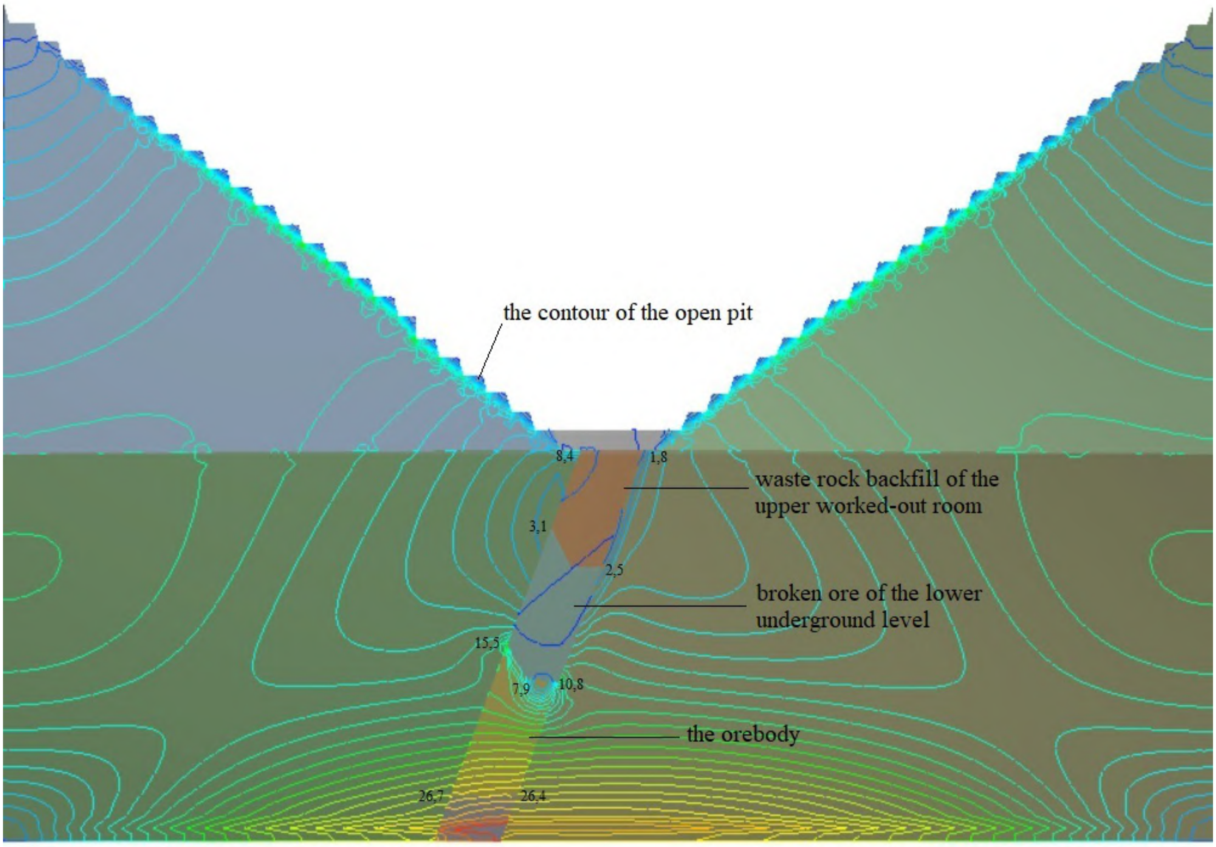

Figure 4. Results of calculation of the main stresses σ_1 when applying open-underground mining of the magnetite quartzites deposit with ore breaking and drawing and subsequent backfilling the stoping space of the worked-out room with waste rocks: 1 – the contour of the open pit; 2 – waste rock backfill of the upper worked-out room; 3 – broken ore of the lower underground level; 4 – the orebody.

In order to improve the technologies of transition from open pit to underground mining of magnetite quartzites, on the example of Kryvyi Rih iron ore basin, three fundamental technological schemes are proposed.

The idea behind the first flowsheet of transition from the open pit to underground method of mining an ore deposit is illustrated in figure 5.

In addition, the proposed solution to store waste rocks in the worked-out space of underground mines has a significant environmental effect, improving the environment of the mining basin.

In the future, in order to develop the environmental safety of the region, it is proposed to store all available waste rock, including overburden at possible parallel ore mining by the open pit method, in the worked-out space of underground mines.

Further underground extraction of magnetite quartzites will be carried out by systems of level caving of ore under overlying waste rocks.

This technology is the cheapest due to no consolidating backfill used that is provided for in the following flowsheets.

The idea behind the second flowsheet of the transition from the open pit to underground method of mining an ore deposit consists in backfilling the stoping space of the room with consolidating backfill after the complete drawing of broken ore. After the consolidating backfill

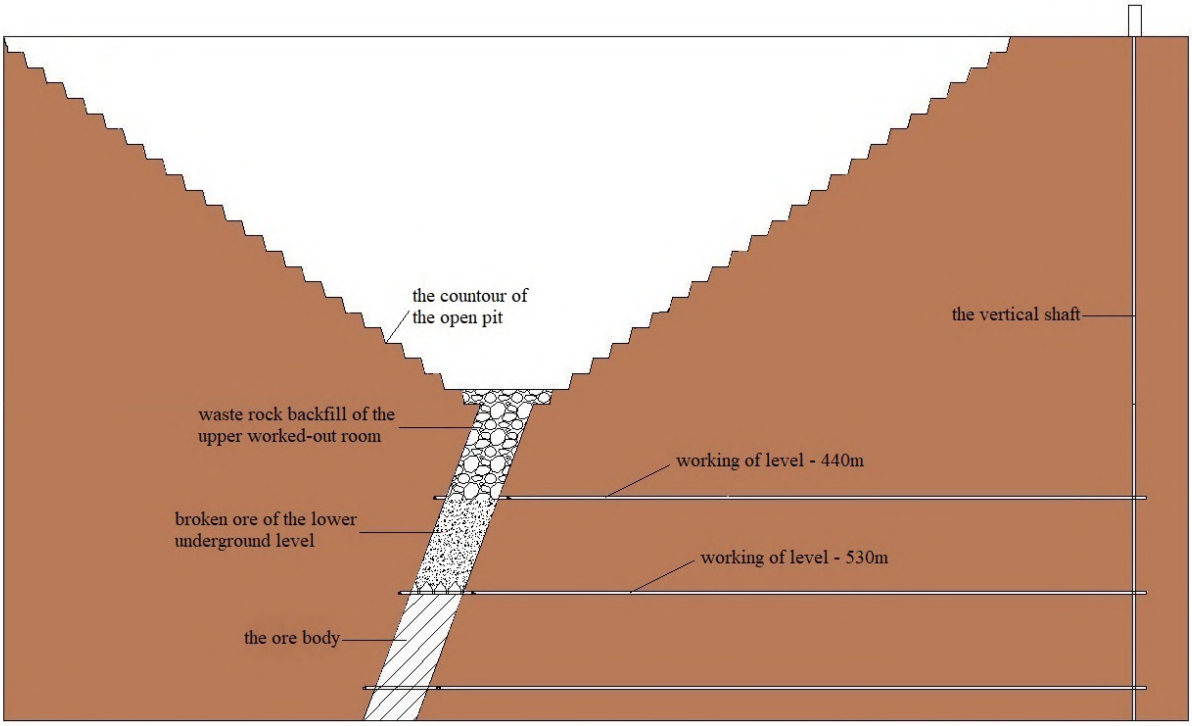

Figure 5. The proposed technology of open pit-underground mining of the deposit of magnetite quartzites with backfilling the worked-out room with waste rocks: 1 – the contour of the open pit, 2 – the vertical shaft, 3 – workings of level – 440m, 4 – workings of level -530 m, 5 – waste rock backfill of the upper worked-out room, 6 – broken ore of the lower underground level, 7 – the orebody.

gains its standard strength, an internal dump of waste rocks can be created on the bottom of the open pit.

Further underground extraction of magnetite quartzites will be carried out by level-room mining under protection of an artificial pillar made of consolidating backfill.

To reduce costs for consolidating backfill in case of its necessary application in the initial version of the combined open pit-underground mining of magnetite quartzites, the third flowsheet with a partial artificial pillar made of consolidating backfill is proposed.

The idea behind the third flowsheet consists in backfilling the bottom of the worked-out room with extra strong consolidating backfill after the complete drawing of broken ore. After the consolidating backfill gains its standard strength, it can be overlaid with waste rocks as an inert backfill.

Formation of an artificial pillar of consolidating backfill on the bottom of the stope requires a much smaller amount of the backfill material. At the transitional stage, this volume can be obtained by using a mobile backfilling complex. Consequently, no need for construction of a stationary backfilling complex significantly reduces the cost of the proposed technology, the cost of magnetite quartzites production by the proposed option of the technology of combined open pit-underground mining.

6. Conclusions

It is determined that nowadays development of deposits of ferruginous quartzites of Kryvbas by underground mining has equaled the cost of open pit operations. At the same time, the cost of open pit operations will steadily increase, but in underground mining it will remain rather stable.

The nature of distribution of the maximum stresses σ_1 in the massif is determined. Mathematical modeling is performed and the results of calculating the main stresses σ_1 are presented in the proposed variantions of the open pit-underground mining of the magnetite quartzites deposit.

It is proved that transition to open pit-underground, and over time to underground mining will reduce environmental tensions in the region.

Highly efficient technologies of transition from open pit extraction of magnetite quartzites to open pit-underground and underground mining of iron ore raw materials within the mining basins of Ukraine are developed and improved.

7. Author contributions

The author contributions are as follows:

- *Mykola Stupnik* conceived the idea of the study, designed the research methodology, and supervised the project.
- *Vsevolod Kalinichenko* performed the numerical simulations, analyzed the data, and wrote the first draft of the manuscript.
- *Olena Kalinichenko* conducted the field experiments, collected and processed the samples, and contributed to the data interpretation.
- *Oleksandr Shepel* assisted with the numerical simulations, and revised the manuscript.
- *Mykhailo Hryshchenko* helped with the field experiments, prepared the figures and tables, and edited the manuscript.

All authors read and approved the final version of the manuscript.

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References

[1] Rudko H I (ed) 2013 *Heoloho-ekonomichna otsinka rodovyshch korysnykh kopalyn Ukrayiny ta problemy nadrokorystuvannya (20 rokiv DKZ)* (Kyyiv–Chernivtsi: Bukrek)
[2] Oleynyk T A 2013 *Zbahachennya korysnykh kopalyn* **97**(56) 18–28
[3] Pysmennyi S, Chukharev S, Khavalbolot K, Bondar I and Ijilmaa J 2021 *E3S Web of Conferences* **280** 08013 URL https://doi.org/10.1051/e3sconf/202128008013
[4] Pysmennyi S, Brovko D, Shwager N, Kasatkina I, Paraniuk D and Serdiuk O 2018 *Eastern-European Journal of Enterprise Technologies* **95**(5) 33–45 URL https://doi.org/10.15587/1729-4061.2018.142483

[5] Khomenko O, Kononenko M, Kovalenko I and Astafiev D 2018 *E3S Web Of Conferences* **60** 00009 URL https://doi.org/10.1051/e3sconf/20186000009
[6] Chernykh A D 1089 Osnovnyye tekhnologicheskiye printsipy kompleksnoy otkryto-podzemnoy razrabotki mestorozhdeniy *Dokl. Vtorogo Vsemirnogo kongr. po nemetellicheskim iskopayemym* vol 2 pp 640–646
[7] Pysmennyi S, Chukharev S, Kyelgyenbai K, Mutambo V and Matsui A 2022 *IOP Conference Series: Earth and Environmental Science* **1049**(1) 012008 URL https://doi.org/10.1088/1755-1315/1049/1/012008
[8] Bazaluk O, Petlovanyi M, Zubko S, Lozynskyi V and Sai K 2021 *Minerals* **11**(8) 858 URL https://doi.org/10.3390/min11080858
[9] Chernykh A D 1984 Sovershenstvovaniye sovmestnoy (otkryto-podzemnoy) razrabotki rudnykh mestorozhdeniy *Tezisy dokladov nauchno-tekhnicheskoy konferentsii* p 223
[10] Krupnik L, Yelemessov K, Bortebayev S and Baskanbayeva D 2018 *Eastern-European Journal of Enterprise Technologies* **96**(12) 22–27 URL https://doi.org/10.15587/1729-4061.2018.151038
[11] Porkuian O, Morkun V, Morkun N and Serdyuk O 2019 *Acta Mechanica et Automatica* **13**(4) 262–270
[12] Kyelgyenbai K, Pysmennyi S, Chukharev S, Purev B and Jambaa I 2021 *E3S Web of Conferences* **280** 08001 URL https://doi.org/10.1051/e3sconf/202128008001
[13] Khomenko O, Rudakov D and Kononenko M 2011 *Technical And Geoinformational Systems In Mining* 271–275 URL https://doi.org/10.1201/b11586-45
[14] Kononenko M, Khomenko O, Savchenko M and Kovalenko I 2019 *Mining Of Mineral Deposits* **13**(3) 22–30 URL https://doi.org/10.33271/mining13.03.022
[15] Bazaluk O, Rysbekov K, Nurpeisova M, Lozynskyi V, Kyrgizbayeva G and Turumbetov T 2022 *Frontiers in Environmental Sciencey* **10** 852591 URL https://doi.org/10.3389/fenvs.2022.852591
[16] Issayeva L, Togizov K, Duczmal-Czernikiewicz A, Kurmangazhina M and Muratkhanov D 2022 *Mining of Mineral Deposits* **16**(2) 14–21 URL https://doi.org/10.33271/mining16.02.014
[17] Antropov B P, Petyakhin V N, Mikhaylov V V and Frolov V I 1986 *Gornyy zhurnal* **6** 18–20
[18] Volkov Y V, Bulatov V F and Popov V Y 1990 *Gornyy zhurnal* **7** 35–37
[19] Bolatova A, Kuttybayev A, Kainazarov A, Hryhoriev Y and Lutsenko S 2022 *Series of geology and technical sciences* **1** 33–38 URL https://doi.org/10.32014/2022.2518-170X.137
[20] Golik V, Komashchenko V, Morkun V and Zaalishvili V 2015 *Metallurgical and Mining Industry* **7**(4) 325–329
[21] Chetverik M S 1998 *Geotekhnicheskaya mekhanika* **10** 183–187
[22] Stupnik M I, Kalinichenko O V and Kalinichenko V O 2012 *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu* **6** 126–130
[23] Stupnik M, Kalinichenko V, Fedko M and Kalinichenko O 2018 *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu* **6** 20–25 URL https://doi.org/10.29202/nvngu/20186/5
[24] Rysbekov K, Bitimbayev M, Akhmetkanov D, Yelemessov K, Barmenshinova M, Toktarov A and Baskanbayeva D 2022 *Mining of Mineral Deposits* **16**(2) 64–72 URL https://doi.org/10.33271/mining16.02.064
[25] Stupnik M, Kalinichenko V, Fedko M, Pysmennyi S, Kalinichenko O and Pochtarev 2022 *Mining of Mineral Deposits* **16**(2) 33–41 URL https://doi.org/10.33271/mining16.02.033

Recognition of mineralogical and technological varieties of iron ore on the basis of ultrasound backscatter spectrograms

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Recognition of mineralogical and technological varieties of iron ore on the basis of ultrasound backscatter spectrograms

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Abstract. The research is aimed to the analysis and modeling of the process of propagation of ultrasonic waves in iron ore samples to assess its mineralogical varieties. The paper analyzes domestic and foreign experience in modeling of ultrasonic waves propagation; methods of mathematical and computer modeling were used, as well as methods of mathematical statistics and probability theory for analysis of the results. Scientific novelty consists in developing and substantiating a method for recognizing the mineralogical and technological varieties of iron ore of a developed deposit based on spectrograms of a backscattered ultrasonic probing signal. Practical valueconsists in developing a methodology for non-contact non-destructive mineralogical analysis of iron ore to improve the efficiency and quality of its further processing and preparation for metallurgical processing. results. As measurable characteristic estimates of textural and structural features of iron ore varieties the results of spectral analysis of the reversed radiant ultrasonic signal were used.To implement the measurement results classification procedure, Adaptive Neuro-Fuzzy Inference System is used. At the vector of parameters of membership functions of terms of input variables and the vector of coefficients of linear functions in the conclusions of the rules was formed based on the characteristics of the processed ore and the spectrograms of the backscattered ultrasonic signal. The average accuracy of recognition of magnetite, chlorite-carbonate-magnetite, hematite-magnetite, magnetite-cummngtonite-chlorite-siderite mineral varieties of iron ore of the studied deposit was 93%.

1. Introduction

Information about the mineralogical varieties of iron ore can be effectively used to improve the quality of its preparation for metallurgical processing [1]. The technologies of mineralogical analysis that exist and are used in practice take a lot of time and require significant labor costs for preparatory operations. Ultrasonic measurement is a widely used tool for the detection, localization and characterization of materials with important applications in many fields [2]. However, the solution of these problems is associated with great difficulties in relation to inhomogeneous media in which the ultrasonic wave is scattered by the microstructure of the material [3]. The data obtained in this case directly from the results of raw measurements is difficult to analyze, since they depend on many interrelated characteristics of the medium under study. In fact, the maximum information that can be experimentally obtained from each area of the material under study consists of the parameters of the transmitted and reflected probing signals. Thus, the actual problem is to substantiate the necessary and sufficient set of estimated characteristics of the process of propagation of ultrasound in randomly inhomogeneous media, as well as the development of effective methods for their processing for operational non-contact non-destructive mineralogical analysis of iron ore.

2. Literature review

Measurement methods based on the evaluation of the characteristics of backscattered ultrasonic waves in the medium under study are widely used [4, 5]. In work [6] a new formulation is presented to derive the absolute backscatter coefficient from pulse echo measurements. The diffraction correction function for measuring the backscattering coefficient and the acoustic coupling function for the echo-pulse system are determined. The elements of these functions are presented for a flat disk transducer and a transducer with spherical focusing. Approximations of these functions are also given. For a flat disk transducer, the final formulation looks like a modification of the well-known Siegelmann-Reid formulation [7]. For a focused transducer, the final correction is a weak function of frequency when the scattering volume is close to the focal region.

Velichko et al [8] proposed to use a set of measurement results to achieve a complete spatiotemporal separation of the data of the transmitter-receiver structure corresponding to different local areas of ultrasonic signal scattering. It is expected that access to local scattering data can provide valuable benefits for many applications. This method makes it possible to use the angular distribution of the scattering amplitude and phase of each local scattering region to detect small inclusions in various highly scattering materials.

To recognize the characteristics of the interaction of elastic vibrations with the medium in which they propagate, many methods have been proposed, for example, cepstral frequency coefficients (MFCC) are widely used, which describe the shape of the spectrum of an acoustic signal [9–11]. The problem is that individual elements of the acoustic interaction signal are noise-like with a wide flat spectrum and may include strong signatures in the time domain. At present, only a few features in the time domain are known to characterize such diverse audio signals. In work [12] an empirical feature analysis is presented to characterize acoustic signals and it is proposed to use a tracking matching (MP) algorithm to obtain effective time-frequency responses. The MP-based method uses a dictionary for feature selection, resulting in a flexible, intuitive, and physically interpretable set of features. The MP-based function is used as an addition to the MFCC functions in order to provide a higher accuracy of recognition of the characteristics of the analyzed environment.

Traditional acoustic event recognition methods based on informative input characteristics or with internal sequencing methods tend to perform poorly in the presence of interfering acoustic noise. Since noise distortion may be unavoidable in practical situations, it is important to develop more robust analysis models and classifiers [13, 14]. Recent advances in this field use powerful machine learning techniques with multivariate input features such as spectrograms or auditory images. They increase reliability largely due to the discriminatory capabilities of internal classifiers. In work [15] new features derived from spectrogram characteristics are proposed, combined with the powerful classification capabilities of a convolutional neural network (CNN). The proposed method demonstrates high performance under noise conditions compared to current approaches to standard acoustic event analysis and recognition problems.

A number of works propose methods for classifying the parameters of acoustic signals based on the support vector machine (SVM) [16–18]. Tran and Li [19] uses a parametric approach to the characterization of acoustic signals based on subband time envelope distribution (STE) and kernel techniques to determine the subband probabilistic distance (SPD) within SVM. It is shown that the generalized gamma model is well suited for characterizing acoustic events, and the determination of the probabilistic distance provides a closed-form solution for calculating the magnitude of the discrepancy, which significantly reduces computational costs. The results show that the proposed classification method is superior to traditional SVM classifiers with Mel-frequency cepstral coefficients (MFCC).

A promising biological method for classifying acoustic events, which combines spike coding with a spike neural network (SNN) [20]. Peak encoding extracts key points that represent the local maximum components of the acoustic spectrogram and are encoded based on their local time-frequency information. Thus, both position information and spectral characteristics are extracted. The proposed method simultaneously increases the sparseness of the acoustic event spectrogram, producing a noise-tolerant representation, and also maximizes the distinguishability of the spike encoding input data in terms of their temporal information [21].

An important element of the analysis of the results of acoustic interaction is the method of its qualitative description. Mesaros et al [3] presents and discusses various metrics proposed for evaluating acoustic event detection systems used in real situations. An overview of the most common metrics in the field and how they are adapted and interpreted in the polyphonic case is presented. Each metric is defined based on segments and events, and the consequences of averaging based on instances and classes are analyzed using a case study.

Acoustic events can occur both as a result of the purposeful formation of a probing signal, and as a side effect [22–24]. In work [25] a concept is presented that uses acoustic signals to classify instrument-tissue interactions during diathermy. This is done by training a CNN classification pipeline based on a logarithmic spectrogram of acoustic signals recorded directly from the operation area. The presented model achieved an accuracy of up to 89.90% on the data set obtained in the experimental setup.

Another use caseacoustic events, as a side effect, is a system toterrain classification implemented as a component of an autonomous mobile robotic system operating in unknown real conditions [26]. Recently, several proprioceptive terrain classification techniques have been developed to improve reliability or act as a fallback to traditional approaches [27, 28]. However, they lack quality adaptation due to various factors including lack of accuracy, reliability, and slow execution times. Valada and Burgard [26] uses the sounds of vehicle interaction with the ground as a proprioceptive modality and proposes a recurrent model based on deep short-term memory that captures both the spatial and temporal dynamics of such an operation. The model has a new convolutional neural network architecture that allows for deep spatial features, and is supplemented with long-term memory to account for complex temporal dynamics. In addition, a training scheme is proposed that takes into account noise effects, which allows you to synthesize generalized models necessary for reliable operation in real conditions.

The tasks of analyzing the characteristics of rocks have much in common with the evaluation of suspension parameters. Heterogeneous mixtures of solids in liquids play an important role in various industries. Online methods for analyzing the concentration and size of solid particles in given suspensions are of great interest in chemistry, mining and processing industries, for example, for monitoring and controlling mineral processing processes [29]. In work [30] a method for determining the concentration and size of particles using a parametric approach is proposed. This is achieved by selecting an analytical model for the spectra of the received echo signals and determining their quantitative parameters. It is shown that the values of amplitude, center frequency and bandwidth, which are obtained from the fitted model, have great potential for evaluating the characteristics of the suspension.

Thus, the development of methods for measuring characteristics, modeling, classification and recognition of randomly inhomogeneous media is an urgent scientific and technical problem. However, the complexity of solving this problem does not allow creating a universal theoretical and software-technical base for practical application in various industries. A promising approach in the implementation of the mineralogical analysis of iron ore is the use of the parameters of the backscattered ultrasonic signal propagating in the studied samples, and modern methods of their interpretation and analysis.

3. Problem statement

The article presents the results of the development, justification and approbation of the method for recognizing the main mineralogical and technological varieties of iron ore of the developed deposit based on the spectrograms of the backscattered ultrasonic probing signal using the ANFIS neuro-fuzzy classifier.

4. Materials and results

In work [31] the characteristic of the mineral composition, as well as the size of mineral formations in the iron ore of magnetite deposits of the Kryvyi Rih basin is given. In the varieties of iron ore, the grains and aggregates that form them are distributed unevenly both in quantity and size. However, they differ with its physico-mechanical and chemical-mineralogical properties. Magnetite is one of the most common minerals in the Kryvyi Rih basin.

It is included in iron ores and ferruginous rocks as an important ore-forming mineral. Tables 1 and 2 show the characteristics of the mineral composition, as well as the size of individuals and aggregates of mineral varieties of hornfelses and jaspilites of the Skelevatsky magnetite deposit (Kryvyi Rih, Ukraine) [31]. The characteristics are given in relation to the main iron-bearing mineral – magnetite and the main accompanying – quartz.

In mineral varieties, individual types of magnetite aggregates are unevenly distributed (table 2) and have different configurations (figure 1).

When ultrasonic waves propagate in a randomly inhomogeneous medium, with the characteristics given in table 1, their attenuation occurs due to the absorption and scattering of elastic vibrations on the mineral formations of iron ore. Fluctuations in the number and size of mineral inclusions in a controlled volume V of the medium under study affect the parameters of the ultrasonic signal measured by the detector D.

Table 1. Characteristics of the mineral composition, as well as the size of individuals and aggregates in iron ore.

Hornfels and Jaspilites	Magnetite			Quartz	
	Size, mm		Content, %	Grain size, mm	Content, %
	grain	unit			
Magnetite	0.15	0.35	90	0.04	8.5
Chlorite-carbonate-magnetite	0.18	0.45	85	0.05	8
Hematite-magnetite	0.15	0.6	87	0.03	5.5
Magnetite-cummingtonite-chlorite-siderite	0.15	0.2	76	0.08	four

Table 2. Distribution of types of magnetite aggregates in iron ore [31].

Hornfels and Jaspilites	Unit type			
	polyhedral	branched	tape	solid and interspersed
Magnetite	50	40	5	5
Chlorite-carbonate-magnetite	50	35	15	0
Hematite-magnetite	80	10	5	5
Magnetite-cummingtonite-chlorite-siderite	60	20	10	10

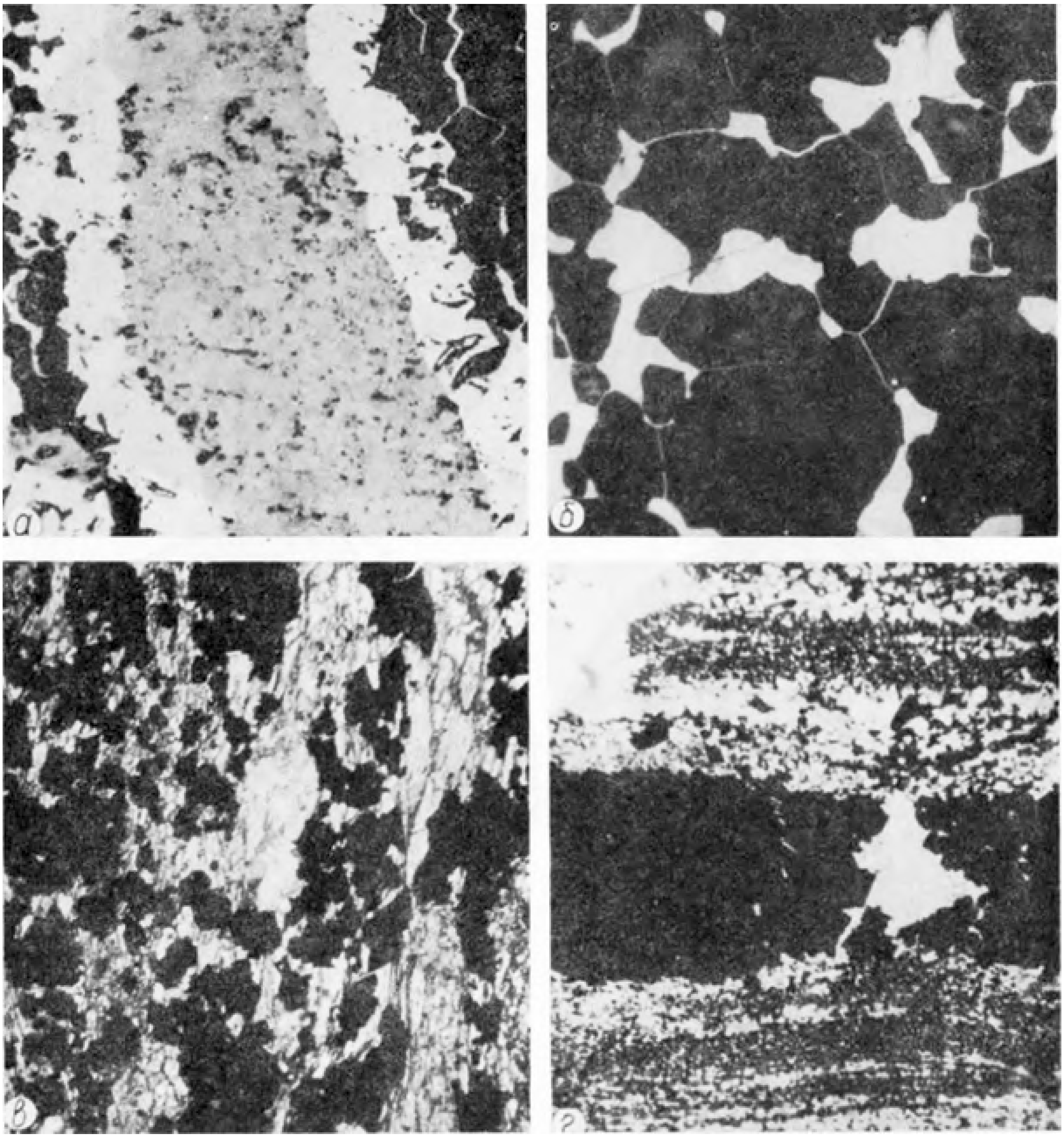

Figure 1. Distribution and configuration of magnetite aggregate types in various varieties of iron ore.

Let us determine the concentration of mineral inclusions of magnetite in the studied sample of iron ore through their number in volume V:

$$n_1 = N_1/V. \tag{1}$$

Since the number of inclusions fluctuates, then N_1 is a random number with Poisson distribution:

$$P_{N1}(k) = \frac{< N_1 >^k e^{-<N_1>}}{k!}, k = 0, 1, 2, ... \tag{2}$$

where $< N_1 >$ is the average value of the number N_1 in the volume V, which can be determined through the average value of the concentration $\vec{n}_1$:

$$< N_1 > \; = \bar{n}_1 V. \tag{3}$$

Then the integral intensity of ultrasonic waves with wavelength λ, passing the distance Z in the medium, will be determined by the expression:

$$I_\lambda^\circ(Z) = I_\lambda \exp\left(-\frac{1}{V}\sum_{i=1}^{N_1}\sigma_p(\lambda, R_i)Z\right), \tag{4}$$

where I_λ is the intensity of the ultrasonic signal emitted into the medium under study; $\sigma_p(\lambda, R)$ is the attenuation cross section of ultrasonic vibrations with a wavelength λ on a mineral inclusion of size R_i.

The detector reading D will be proportional to the value $I_\lambda^\circ(Z)$, averaged over fluctuations in the number and size of inclusions, i.e. in proportion to the value:

$$< I_\lambda^\circ(Z) >= I_\lambda < \exp\left\{-\frac{1}{V}\sum_{i=1}^{N_1}\sigma_p(\lambda, R_i)Z\right\} >, \tag{5}$$

Denote by ξ random variable:

$$\xi = \exp\left\{-\frac{1}{V}\sum_{i=1}^{N_1}\sigma_p(\lambda, R_i)Z\right\}. \tag{6}$$

To find the average value of the ξ apply the formula for the total mathematical expectation:

$$M\xi = \sum_{k=0}^{\infty} M\left(\frac{\xi}{k}\right)P_{N_1}(k). \tag{7}$$

In this expression $M\left(\frac{\xi}{k}\right)$ stands for conditional expectation. It is easy to show that:

$$M\left(\frac{\xi}{k}\right) = \left[M\exp\left\{-\frac{1}{V}\sigma_p(\lambda, R)Z\right\}\right]^k, \tag{8}$$

where:

$$M\exp\left\{-\frac{1}{V}\sigma_p(\lambda, R)Z\right\} = \int_0^\infty \exp\left\{-\frac{Z}{V}\sigma_p(\lambda, R)Z\right\}f(R)dR = \eta_1. \tag{9}$$

Here $f(R)$ is a distribution function of mineral inclusions by size.

Substituting expressions (2) and (9) into (7), we obtain

$$M\xi = \sum_{k=0}^{\infty} \cdot\eta_1^k \frac{(n_1 V)^k}{k!}e^{-\bar{n}_1 V} = e^{-\bar{n}v}\exp\{\bar{n}_1 V\eta_1\} = e^{-\bar{n}_1 V(1-\eta_1)}. \tag{10}$$

In the same way, the influence of fluctuations in the concentration and size distribution of other mineral formations on the intensity of the ultrasonic signal propagating in the rock can be determined.

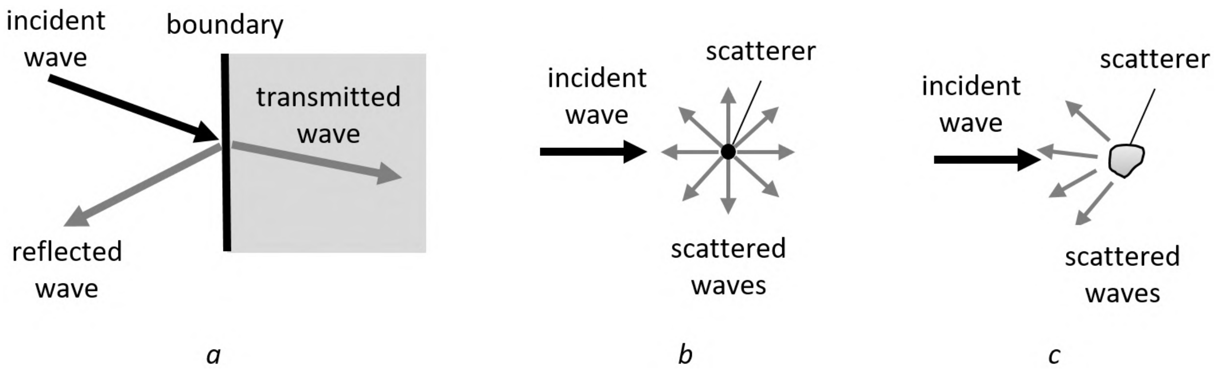

Figure 2. Types of ultrasound scattering in an inhomogeneous medium.

In the expression (4) attenuation cross section of ultrasonic vibrations with wavelength λ is the sum of two terms:

$$\sigma_p(\lambda, R) = \sigma_c(\lambda, R) + \sigma_s(\lambda, R), \tag{11}$$

where $\sigma_c(\lambda, R)$ is the absorption cross section; $\sigma_s(\lambda, R)$ is the scattering cross section.

Let us consider in more detail the scattering of ultrasonic waves on mineral inclusions in iron ore. On figure 2 it is shown the types of ultrasound scattering depending on the ratio of its wavelength and the size of the scattering structure [32].

Specular scattering (figure 2, a) occurs when an object is much larger than the ultrasound wavelength. The ultrasonic wave can be reflected or refracted through the boundary between the object and its environment. Diffuse scattering (figure 2, b) occurs when the structure is much smaller than the ultrasound wavelength. Diffraction scattering (figure 2, c) occurs when the wavelength and size of the object are comparable. In this case, the incident wave scatters equally in all directions.

We will assume that the electrical transducer of ultrasonic waves combines the functions of transmission (generation) and reception of ultrasonic waves. In the transmission mode, the transducer surface is driven into oscillation by electrical excitation, and at the same time, a falling pressure field $P_{in}(\mathbf{r}; w)$ is formed at the point $\mathbf{r}$ of the medium under study [6]:

$$P_{in}\left(\mathbf{r}w\right) = P_0(w) D_T(\mathbf{r}; w)), \tag{12}$$

where $P_0(w)$ is the pressure amplitude on the transducer surface; $D_T(\mathbf{r}; w)$ is the transducer directivity diagram; $w = 2\pi f$ is the angular frequency of the acoustic wave.

Using the electrical equivalent [6], can be written:

$$\left\langle |V_s\left(\mathbf{r} \in V; w\right)|^2 \right\rangle = |V_{in}(w) \bullet X_T(w) \bullet X_R(w)|^2 \bullet \theta(w) \bullet \overline{l \bullet D_s}(\mathbf{r} \in V; w), \tag{13}$$

where $V_s\left(\mathbf{r} \in V; w\right)$ is the received voltage signal from the scattering volume; $V_{in}(w)$ – electrical signal that excites the transducer; $X_T(w) = P_0(w)/V_{in}(w)$ – coefficient of electromechanical connection of the transducer in the transmission mode; $X_R(w) = V_s(\mathbf{r}; w)/\overline{P_s}\left(\mathbf{r}; w\right)$ – coefficient of electromechanical coupling of the transducer in the receive mode.

Since $\overline{D_s}(\mathbf{r} \in V; w)$ can be obtained both analytically and numerically, the backscatter coefficient $\theta(w)$ can be calculated if the system response function $|V_{in}(w) \bullet X_T(w) \bullet X_R(w)|^2$ is defined. In work [7] the response function of the system is measured by placing a reference plate with an ideal reflective surface at the location of the sample volume. There are techniques based on placing the reference plate at half this distance, as well as in the near field for a flat transducer and in the geometric focal plane for a focused transducer [4].

Assuming that the received signal is integrated over the surface of the receiver, and $\frac{U_R(\mathbf{r}_R;w)}{U(w)}$ is the relative sensitivity of the receiving element with coordinates $\mathbf{r}_R$, we can write:

$$D_{ref}\left(2z_{ref};w\right)=\frac{\exp\left(-2ikz_{ref}\right)}{S_R}\int\limits_{S_R}\frac{U_R\left(\mathbf{r}_R;w\right)}{U(w)}D_T\left(2z_{ref};w\right)dS(\mathbf{r}_R). \tag{14}$$

This expression defines the acoustic coupling function from the transducer surface (S_R – active transducer area) to the reference plane and back to the transducer surface [33].

Using the same electromechanical coupling coefficients, the output voltage of the converter due to the reflected wave:

$$V_{ref}\left(z_{ref};w\right)=V_{in}(w)X_T(w)X_R(w)\exp(i2kz_{ref})D_{ref}(2z_{ref};w). \tag{15}$$

Taking into account (13) and (15), it is possible to determine the backscattering coefficient of ultrasonic waves:

$$\theta(w)=\frac{\left\langle|V_s(\mathbf{r}\in V;w)|^2\right\rangle}{|V_{ref}(2z_{ref};w)|^2}\bullet\frac{|D_{ref}(2z_{ref};w)|^2}{l\bullet\overline{D_s}\left(\mathbf{r}\in V;w\right)}. \tag{16}$$

As follows from the above expressions, the parameters of the process of scattering of ultrasound on the structural inhomogeneities of the medium characterize its structural and textural properties. This allows them to be used to recognize the main mineralogical and technological varieties of iron ore in relation to certain of its deposits [34].

The scheme of functioning of the system for recognition of mineralogical and technological varieties of iron ore is shown in figure 3. The functioning algorithm includes the processing of ultrasonic signals and annotations, as well as training the recognition system [3]. Acoustic characteristics are extracted from the measurement results, and at the training stage, a correspondence is found between them and the characteristics of the iron ore samples indicated in the annotations. The testing chain includes processing test signals as for training, testing the system, and, if necessary, post-processing the output of the system to obtain a representation similar to annotations.

In practice, there are three main methods for analyzing acoustic signals in the clock and frequency domains. The watch area has parameters that are taken from the statistics of the output. In the frequency domain, Four's transformations are performed for frequency spectroscopy and cepstral analysis [35]. Let's look at the possibility of victorious results in the

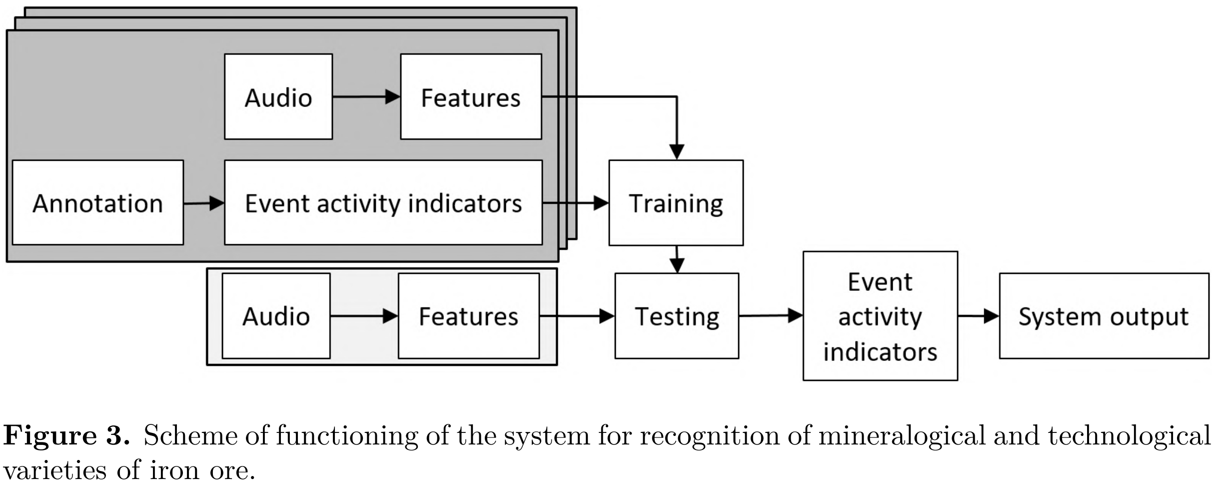

Figure 3. Scheme of functioning of the system for recognition of mineralogical and technological varieties of iron ore.

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spectral analysis of the turning pink ultrasonic signal for the task of recognizing the mineralogy and technological diversity of the flood.

Spectrograms are two-dimensional visualizations of spectral sequences with time on the abscissa and frequency on the ordinate. The color intensity of each pixel is related to the amplitude of the corresponding frequency. When ultrasonic waves propagate in a rock, due to their multiple reflection and scattering on mineral formations, a spectral characteristic of the medium in which they propagate is formed. Thus, the spectrogram of a backscattered probing signal is a spatial (in a certain area) amplitude-frequency characteristic of the medium under study or its acoustic structural-textural image.

To obtain spectrograms in accordance with the methodology used in the works [25, 26], a short-time Fourier transform (STFT) was performed for each window segment of the recorded probing signal:

$$X\ (i,\ j) = \sum_{p=0}^{N_f-1} x[n]w[n-j]\exp\left(-p\frac{2\pi k}{N_f}n\right), p = 0, \ldots, N_f - 1, \tag{17}$$

where $x[n]$ is the signal consisting of N_f samples, $w[n-j]$ is the window function in frame $n-j$, p are iteration variables, $2\pi k$ is the frequency.

In this expression, $X(i;j)$ is the matrix representation of the spectrogram of the received signal with $f(k) = kf_s/N_f$; $x[n]$ is the recorded raw received signal with sample length N_f and sampling rate f_s. The sliding window step size was set to 512 samples, resulting in a window overlap of 50%.

To compensate for the Gibbs effect during STFT by smoothing out discontinuities at the beginning and end of the received signal, the Hamming window function was used:

$$w[n] = 0.54 - 0.46\cos\left(2\pi\frac{n}{M-1}\right), n = 0, \ldots,\ M-1. \tag{18}$$

Then the power spectrum log is calculated:

$$S_{\log}(i,j) = 20\log_{10}(|X(i,j)|). \tag{19}$$

In order to reduce the effect of disturbing noise effects, the spectrograms are normalized by dividing by the maximum amplitude.

$$S(i;j) = S_{\log}(i,j)/\max S_{\log}(i,j). \tag{20}$$

Then the average spectrum over the entire data set is calculated and subtracted from the normalized spectrogram.

On figure 4 it is shown spectrograms of various mineral varieties of iron ore: the x-axis represents time, (ms); y-axis – frequency scale, (Hz); pixel intensity – amplitude, (dB).

As shown in work [36], due to the peculiarities of acoustic interaction, spectrograms provide qualitative characteristics of the classification of research objects.

To implement this procedure, ANFIS (Adaptive Neuro-Fuzzy Inference System) is used – the editor of the Matlab package.In the task of recognizing the main varieties of iron ore of the developed deposit, the vector of parameters of the membership functions of the terms of the input variables and the vector of coefficients of linear functions in the conclusions of the rules are formedbased on the characteristics of the processed ore and the spectrograms of the backscattered ultrasonic signal. ANFIS – the editor automatically synthesizes a neuro-fuzzy network from experimental data, which can be considered as one of the varieties of fuzzy inference of the typeTakagi-Sugeno.

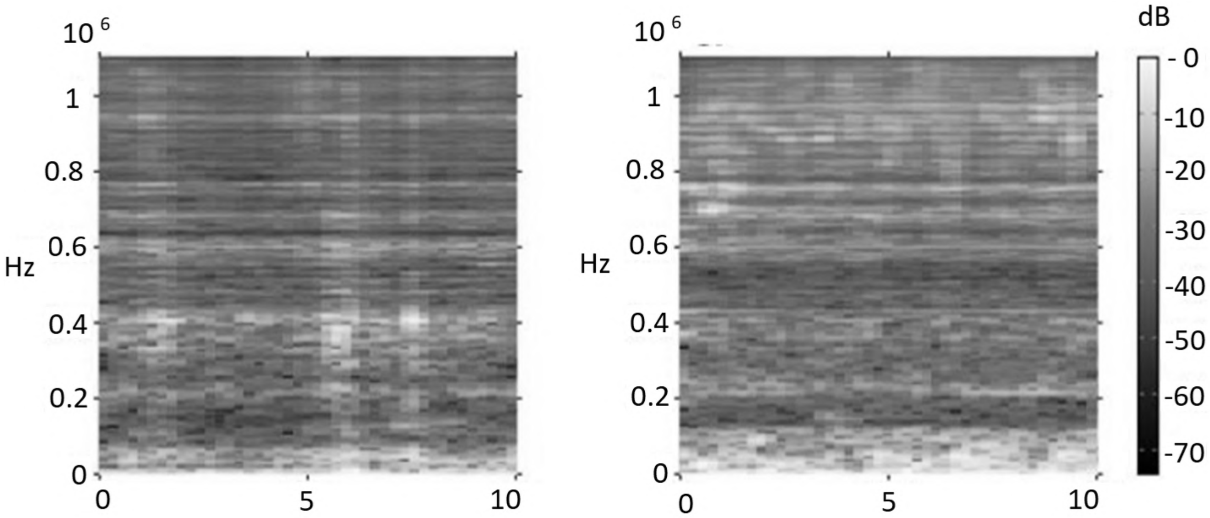

Figure 4. Spectrograms of various mineral varieties of iron ore.

In the process of approbation of the used recognition method, we evaluatedadding the number of epochs of learning, types and number of functions of occurrence of input fuzzy terms in the ANFIS-model for the accuracy of classification.

To study the influence of the number of training epochs of the ANFIS model, the following constant parameters were adopted: the number of input functions of the membership of fuzzy terms – 3; type of input membership functions – bell-shaped (‘gbellmf’); the type of output membership functions is linear (‘linear’) – the only possible option for fuzzy Sugeno-type derivation. Classification accuracy and time spent on model training were calculated. The results of this experiment are shown on figure 5.

With the number of epochs 20 spent 6.9512 s for training. During training for 50 epochs – 11.7630 s were spent. At the same time, the accuracy increases from 0.9410 to 0.9524. A conclusion was made regarding the expediency of further researching the model by training it for 20 epochs.

In the process of researching the influence of the types of membership functions of the input fuzzy terms of the ANFIS model, the following constant parameters were adopted: the number of learning epochs – 20; the number of input functions belonging to fuzzy terms is 3; type of output membership functions – linear (‘linear’). The type of input membership functions that were investigated is given in table 3.

Table 3. Type of studied input membership functions.

“gbellmf”	Generalized bell-shaped membership function
“gaussmf”	Gaussian membership function
“gauss2mf”	Gaussian combination membership function
“trimf”	triangular membership
“trapmf”	Trapezoidal membership

The results of the study of the influence of the types of membership functions of the input fuzzy terms of the ANFIS model on the classification accuracy and the time spent on training the model are shown in figure 6.

Among the tested membership functions, the best results were shown by the bell-shaped

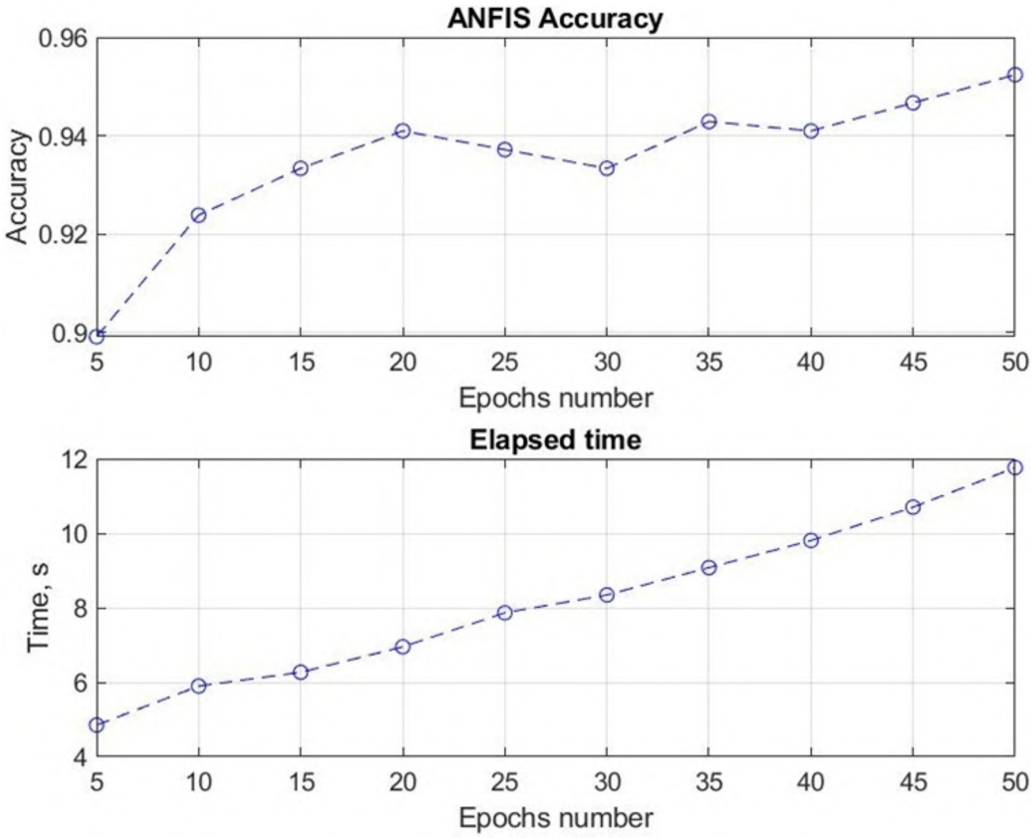

Figure 5. The influence of the number of epochs of ANFIS model training on classification accuracy and time spent on training.

function – accuracy 0.94. At the same time, it also shows one of the best results – 7.13 in terms of duration of study. Therefore, the choice is made in favor of the bell-shaped (Bell-shaped) function of the membership of the terms of the input variables.

In the process of studying the influence of the number of membership functions of the input fuzzy terms of the ANFIS model on the classification accuracy and the time spent on training, the following constant parameters were adopted: the number of training epochs – 20; type of input membership functions – bell-shaped ('gbellmf'); type of output membership functions – linear ('linear'). Variable parameters: the number of fuzzy terms of the input membership functions (2, 3, 4, 5).

The results of calculations of the influence of the number of membership functions of the input fuzzy terms of the ANFIS model on the classification accuracy and the time spent on training are given in the table 4. The option with four membership functions is selected.

Table 4. The influence of the number of membership functions of the input fuzzy terms of the ANFIS model on the classification accuracy and the time spent on training.

Number of functions	Accuracy	Time, s
2	0.777143	1.013732
3	0.940952	6.795064
4	0.966190	47.14676
5	0.968095	291.4074

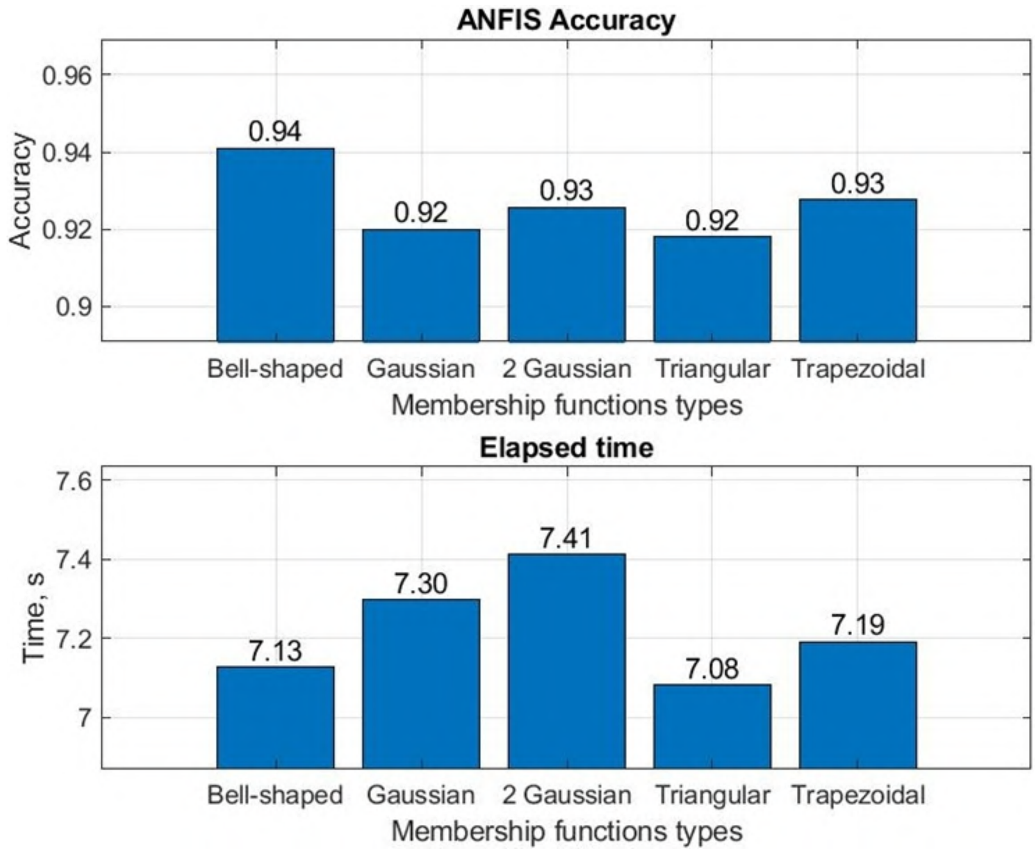

Figure 6. The influence of the types of membership functions of the input fuzzy terms of the ANFIS model on the accuracy of classification and the time spent on training.

Therefore, a model trained for 20 epochs out of 4 was further investigated bell-shaped membership functions of the input fuzzy terms of the ANFIS model.

The average accuracy of recognition of magnetite, chlorite-carbonate-magnetite, hematite-magnetite, magnetite-kummngtonite-chlorite-siderite mineral varieties of iron ore, the characteristics of which are given in tables 1 and 2 was 93%.

5. Conclusions and further research

As measurable characteristic estimates of textural and structural features of iron ore varietiesthe results of spectral analysis of the reversed radiant ultrasonic signal were used.

To implement the measurement results classification procedure, ANFIS (Adaptive Neuro-Fuzzy Inference System) is used – the editor of the Matlab package. At the vector of parameters of membership functions of terms of input variables and the vector of coefficients of linear functions in the conclusions of the rules was formedbased on the characteristics of the processed ore and the spectrograms of the backscattered ultrasonic signal.

The average accuracy of recognition of magnetite, chlorite-carbonate-magnetite, hematite-magnetite, magnetite-cummngtonite-chlorite-siderite mineral varieties of iron ore of the studied deposit was 93%.

Due to the variety of physical-mechanical and chemical-mineralogical characteristics of rocks, the proposed method for recognizing the mineral varieties of iron ore requires tuning the ANFIS model on samples of a particular deposit. To increase the possibility of its more universal use, it is necessary to increase the number of characteristic parameters used to build the model. It is also advisable to consider more advanced methods for building and training the used model, for example, convolutional neural networks (CNN), transfer learning, etc.

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References
[1] Krolop P, Niiranen K, Gilbricht S and Seifert T 2022 *Mineral Processing and Extractive Metallurgy Review* **43**(8) 1014–1020 URL https://doi.org/10.1080/08827508.2021.2023519
[2] Tron V, Haponenko A, Haponenko I and Paranyuk D 2020 *E3S Web of Conferences* **201** 01025 URL https://doi.org/10.1051/e3sconf/202020101025
[3] Mesaros A, Heittola T and Virtanen T 2016 *Applied Sciences* **6**(6) 162 ISSN 2076-3417 URL https://doi.org/10.3390/app6060162
[4] AIUM Standards Committee 1991 *Standard Methods for Measuring Performance of PulseEcho Ultrasound Imaging Equipment* (American Institute of Ultrasound in Medicine)
[5] Campbell J A and Waag R C 1983 *The Journal of the Acoustical Society of America* **74**(2) 393–399 ISSN 0001-4966 URL https://doi.org/10.1121/1.389832
[6] Chen X, Phillips D, Schwarz K, Mottley J and Parker K 1997 *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control* **44**(2) 515–525 URL https://doi.org/10.1109/58.585136
[7] Sigelmann R A and Reid J M 2005 *The Journal of the Acoustical Society of America* **53**(5) 1351–1355 ISSN 0001-4966 URL https://doi.org/10.1121/1.1913479
[8] Velichko A, Villaverde E L and Croxford A J 2021 *Scientific Reports* **11**(1) 993 ISSN 2045-2322 URL https://doi.org/10.1038/s41598-020-79617-z
[9] Bardeli R, Wolff D, Kurth F, Koch M, Tauchert K H and Frommolt K H 2010 *Pattern Recognition Letters* **31**(12) 1524–1534 ISSN 0167-8655 Pattern Recognition of Non-Speech Audio URL https://doi.org/10.1016/j.patrec.2009.09.014
[10] Chu S, Narayanan S and Kuo C C J 2009 *IEEE Transactions on Audio, Speech, and Language Processing* **17**(6) 1142–1158 URL https://doi.org/10.1109/TASL.2009.2017438
[11] Cowling M and Sitte R 2003 *Pattern Recognition Letters* **24**(15) 2895–2907 ISSN 0167-8655 URL https://doi.org/10.1016/S0167-8655(03)00147-8
[12] Chachada S and Kuo C C J 2013 Environmental sound recognition: A survey *2013 Asia-Pacific Signal and Information Processing Association Annual Summit and Conference* pp 1–9 URL https://doi.org/10.1109/APSIPA.2013.6694338
[13] Kotov I, Suvorov O and Serdiuk O 2019 *Eastern-European Journal of Enterprise Technologies* (2(4-98)) 38–47 URL https://doi.org/10.15587/1729-4061.2019.155410
[14] Porkuian O, Morkun V, Morkun N and Serdyuk O 3919 *Acta Mechanica et Automatica* **13**(4) 262–270 URL https://doi.org/10.2478/ama-2019-0036
[15] Zhang H, McLoughlin I and Song Y 2015 Robust sound event recognition using convolutional neural networks *2015 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)* pp 559–563 URL https://doi.org/10.1109/ICASSP.2015.7178031
[16] Chapelle O, Haffner P and Vapnik V N 1999 *IEEE Transactions on Neural Networks* **10**(5) 1055–1064 URL https://doi.org/10.1109/72.788646
[17] Campbell W M, Sturim D E and Reynolds D A 2006 *IEEE Signal Processing Letters* **13**(5) 308–311 URL https://doi.org/10.1109/LSP.2006.870086
[18] Fung G and Mangasarian O L 2001 Proximal Support Vector Machine Classifiers *Proceedings of the Seventh ACM SIGKDD International Conference on Knowledge Discovery and Data Mining* KDD '01 (New York, NY, USA: Association for Computing Machinery) p 77–86 ISBN 158113391X URL https://doi.org/10.1145/502512.502527

[19] Tran H D and Li H 2011 *IEEE Transactions on Audio, Speech, and Language Processing* **19**(6) 1556–1568 URL https://doi.org/10.1109/TASL.2010.2093519
[20] Cao Y, Chen Y and Khosla D 2015 *International Journal of Computer Vision* **113**(1) 54–66 ISSN 1573-1405 URL https://doi.org/10.1007/s11263-014-0788-3
[21] Dennis J, Huy Dat T and Li H 2015 Combining robust spike coding with spiking neural networks for sound event classification *2015 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)* pp 176–180 URL https://doi.org/10.1109/ICASSP.2015.7177955
[22] Li J, Dai W, Metze F, Qu S and Das S 2017 A comparison of deep learning methods for environmental sound detection *2017 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)* pp 126–130 URL https://doi.org/10.1109/ICASSP.2017.7952131
[23] Cakir E, Heittola T, Huttunen H and Virtanen T 2015 Polyphonic sound event detection using multi label deep neural networks *2015 International Joint Conference on Neural Networks (IJCNN)* pp 1–7 URL https://doi.org/10.1109/IJCNN.2015.7280624
[24] Tishchenko S, Eremenko G, Kukharenko O, Pikilnyak A and Gaponenko I 2015 *Metallurgical and Mining Industry* **7**(8) 564–56 URL https://www.metaljournal.com.ua/assets/Journal/english-edition/MMI_2015_8/090Tishchenko.pdf
[25] Ostler D, Seibold M, Fuchtmann J, Samm N, Feussner H, Wilhelm D and Navab N 2020 *International Journal of Computer Assisted Radiology and Surgery* **15**(5) 771–779 ISSN 1861-6429 URL https://doi.org/10.1007/s11548-020-02146-7
[26] Valada A and Burgard W 2017 *The International Journal of Robotics Research* **36**(13-14) 1521–1539 URL https://doi.org/10.1177/0278364917727062
[27] Brooks C A and Iagnemma K D 2007 Self-Supervised Classification for Planetary Rover Terrain Sensing *2007 IEEE Aerospace Conference* pp 1–9 URL https://doi.org/10.1109/AERO.2007.352693
[28] Christie J and Kottege N 2016 Acoustics based terrain classification for legged robots *2016 IEEE International Conference on Robotics and Automation (ICRA)* pp 3596–3603 URL https://doi.org/10.1109/ICRA.2016.7487543
[29] Morkun V, Morkun N and Tron V 2015 *Metallurgical and Mining Industry* **7**(8) 18–21 URL http://ds.knu.edu.ua/jspui/bitstream/123456789/2262/1/Morkun%20V.%20Distributed%20control%20of%20ore%20beneficiation%20interrelated%20processes.pdf
[30] Vogt M and Deilmann M 2019 5.3.3 Parametric spectrum analysis of backscattered ultrasound signals for the characterization of particles in suspensions *20. GMA/ITG-Fachtagung Sensoren und Messsysteme 2019 2019-06-25 - 2019-06-26 Nürnberg, Germany* pp 436–443 ISBN 978-3-9819376-0-2 URL https://doi.org/10.5162/sensoren2019/5.3.3
[31] Lazarenko E K 1977 *Mineralogy of the Krivoy Rog basin* (Kyiv: Naukova dumka)
[32] Mercado K P E 2015 *Developing High-Frequency Quantitative Ultrasound Techniques to Characterize Three-Dimensional Engineered Tissues* Ph.D. thesis University of Rochester URL https://www.researchgate.net/publication/280444277
[33] Chen X, Schwarz K Q and Parker K J 1994 *The Journal of the Acoustical Society of America* **95**(6) 3049–3054 ISSN 0001-4966 URL https://doi.org/10.1121/1.409996
[34] Golik V, Morkun V, Morkun N and Gaponenko I 2018 *Mining of Mineral Deposits* **12**(3) 63–70 URL https://doi.org/10.15407/mining12.03.063
[35] Hysi E, Fadhel M N, Moore M J, Zalev J, Strohm E M and Kolios M C 2019 *Photoacoustics* **14** 37–48 ISSN 2213-5979 URL https://doi.org/10.1016/j.pacs.2019.02.002
[36] Purwins H, Li B, Virtanen T, Schlüter J, Chang S Y and Sainath T 2019 *IEEE Journal of Selected Topics in Signal Processing* **13**(2) 206–219 URL https://doi.org/10.1109/JSTSP.2019.2908700

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Engineering method for predicting the displacement of the earth's surface under the influence of stope workings of coal mines

Engineering method for predicting the displacement of the earth's surface under the influence of stope workings of coal mines

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Abstract. The development of a sufficiently reliable forecast of the values of trough parameters on the earth's surface and the displacement of undermined rocks using mathematical modeling methods is an urgent problem for mining. Not only the protection of objects on the earth's surface depends on its successful solution, but also the choice of the location of mine workings and rational ways to protect them from the influence of rock pressure, the forecast of gas release from undermined sources, the occurrence of gas-dynamic phenomena, the rationale for rational ventilation schemes for excavation areas, the calculation of the bearing capacity supports and many other engineering tasks. The study is based on the use of experimental data obtained during the operation of a separate extraction area, respectively, at the first stage when the working face is removed from the split furnace and at the second stage above the working face when it is sufficiently removed from the open working. This makes it possible to obtain all the necessary experimental data for constructing a general scheme for the development of clearing operations and the formation of a trough for the displacement of the earth's surface in two stages. On the basis of the studies carried out, it was found that the maximum subsidence of the earth's surface above the cut working with a sufficient distance from the production face is equal to the subsidence above the production face at the stage of attenuation of the processes of displacement of undermined rocks and the earth's surface. This gives grounds to make an assumption about the closeness of the displacement parameters of the stationary and dynamic semitroughs.

1. Problem statement

Conducting cleaning operations in coal mines, even at depths of more than 1000 m, has an impact on changes in the state of the earth's surface. Initially, the study of the processes of formation of shear troughs on the earth's surface was aimed at solving one problem -of protecting buildings, structures and other objects from destruction and the harmful effects of mine workings [1–4]. Based on the results of these studies, a regulatory document [5] was developed, which regulated the rules for protecting structures and natural objects from the harmful effects of underground mine workings. Currently, in the coal mines of Ukraine, the requirements of the current rules [6] are mandatory for use, which determine only the conditions for underworking earth's surface. The calculation of displacements and deformations of the earth's surface and rock mass is a complex problem that has not yet received its fundamental solution. For this reason, empirical calculation methods and separate analytical dependencies are used in practice. In recent years, taking into account the possibilities of computer technology, mathematical modeling of the processes of shifting underworked rocks and the earth's surface. This direction of scientific research is the most promising and relevant, since its implementation does not require long and laborious observations both on the earth's surface and in mine workings.

In addition, such an approach to solving the issue under consideration makes it possible to significantly expand the range of engineering tasks to be solved, related not only to the protection of objects on the earth's surface, but also to the safety of mining operations and the manifestation of rock pressure on the lining of workings. The development of a sufficiently reliable forecast of the values of trough parameters on the earth's surface and the displacement of undermined rocks using mathematical modeling methods is an urgent problem for mining. Not only the protection of objects on the earth's surface depends on its successful solution, but also the choice of the location of mine workings and rational ways to protect them from the influence of rock pressure, the forecast of gas release from undermined sources, the occurrence of gas-dynamic phenomena, the rationale for rational ventilation schemes for excavation areas, the calculation of the bearing capacity supports and many other engineering tasks.

In the general case, the formation of a shear trough on the earth's surface consists of two stages [5, 6]. The first is related to the start of operation of the excavation area and the development of stope work when separating the stope from the open cut. At this stage, the process of shifting the undermined rocks of the earth's surface is achieved and a stationary half-trough is formed above the open cut. The second characterizes the shift of the undermined rocks and the earth's surface above the moving stope. The relationship between the stages of the formation of a shear trough on the earth's surface and the development of stopping operations in the excavation area is characterized [7] by a graph (figure 1).

Normative documents [5, 6] do not consider the logical transition from the first stage of the formation of the trough of the earth's surface displacement to the second. In addition, there are ambiguous recommendations for determining individual parameters. It is envisaged that the stage of attenuation of the process of shifting the earth's surface ends when the stope is removed from the projection considered point at a distance that exceeds the depth of work (H) by 1.2÷1.4 times. There is also no exact definition of the location of the point of the beginning of the displacement of the earth's surface.

By a similar principle, mathematical models have been constructed that separately describe the processes of displacement of the earth's surface at different stages of the development of clearing operations. At the initial stage of operation of the excavation area, the maximum subsidence of the earth's surface (η_m) is considered when the stope is removed from the open cut [8]. In parallel with this, mathematical models [9–11] make it possible to predict the subsidence of points on the earth's surface above the stope in time, when its advance no longer has a significant effect on the maximum subsidence of the earth's surface.

Preliminary analysis [12, 13] based on the processing of experimental data [4, 8, 14–18] showed that in some mining and geological conditions, with little changing values of the thickness of the developed seam (m), the depth of mining operations (H) and strength properties undermined rocks, maximum subsidence of points on the earth's surface η_m (Figure 1, curve 8) is close to functional dependence on the distance (L_p) of the stope from the cut working:

$$\eta_m = a_p - b_p \cdot \exp(c_p \cdot L_p) \tag{1}$$

where a_p, b_p, c_p are empirical coefficients typical for some mining-geological and mining-technical conditions. In addition to the least squares method, to determine the coefficients a_p, b_p, c_p of equation 1, the following equations were proposed [12, 13]:

$$a_p = 374 + 7.4 \cdot 10^4 \cdot \frac{m}{H}, r = 0.78 \tag{2}$$

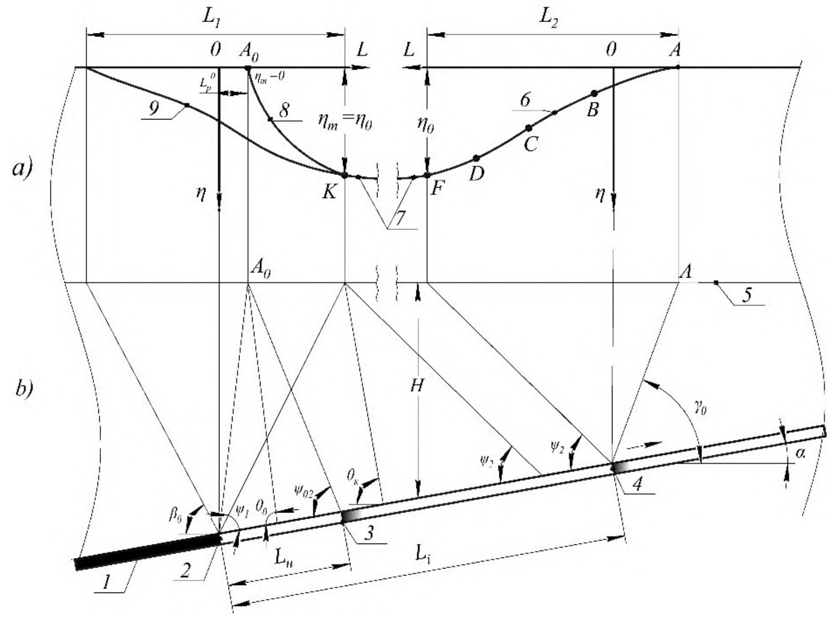


Figure 1. Scheme of the formation of a trough of the earth's surface displacement (a) and its correspondence to the parameters of stopes and the displacement of rocks (b). 1 – the developed layer; 2 – split production; 3 – the position of the treatment face relatively to the split furnace at which the movement of the earth surface begins ($\eta_m = 0$); 4 – *i-e* position of the treatment face after a complete study of the earth's surface (formation of a flat bottom of the mold); 5 – the earth's surface; 6 – dynamic half – mold over the treatment face; 7 – flat bottom of the mold movement; 8 – the trajectory of the maximum points of the earth surface subsidence; 9 – stationary half- mold from the side of the split furnace; β_0, γ_0 – boundary angles, respectively, from the fall and rise of the formation; ψ_1, ψ_2 – angles of complete displacements, respectively, from the fall and rise of the formation; – the angle of full displacements, corresponding to the beginning of the displacement of the earth's surface when removing the face from the split production at a distance; L_H, θ_0, θ_k – the angles of maximum subsidence, respectively, when the processes of displacement of the earth's surface rocks ($\eta_m = 0$) and the formation of a flat bottom ($\eta_m = \eta_0$) ; H – the average depth of conducting cleaning works; α- the angle of the fall of the formation; η, η_m – respectively, subsidence and maximum subsidence of the earth's surface; η_0 – the depth of the flat bottom of the mold ; A_0, A – points of the beginning of the movement of the earth's surface, respectively, is a distance from the split furnace with leaning face and in front of it; *B, C, D, F* – the characteristic point displacement under the influence of clearing face movement; $\longrightarrow$ – is a direction of clearing face movement.

$$b_p = 717 - 41 \cdot v_{ox}, r = 0.96 \tag{3}$$

$$c_p = \frac{1}{-0.5 \cdot H + 14.6}, R = 0.90 \tag{4}$$

where v_{ox} – speed of advancement of the stope, m/month; r and R – respectively, the correlation coefficient and the correlation ratio.

For an analytical description of the dynamics of subsidence of the earth's surface under the influence of a moving stope, it was previously proposed to use logistic [7], exponential [9], or hyperbolic tangent [10] dependences. Comparative analysis of these dependences showed approximately the same, almost functional, convergence with experimental data.

Above the stope, the subsidence of the earth's surface (η_{ox}) in the case of applying the logistic curve, corresponds to the equation:

$$c_p = \frac{a_{ox}}{1 + b_{ox} \cdot \exp(c_{ox} \cdot L_{ox})} \tag{5}$$

where L_{ox} – is the distance from the projection of a point on the earth's surface to the production face, m.

The coefficients a_p, b_p, c_p of equation (5) are also determined in two ways – by the least squares method and using the results of the correlation analysis between the displacement trough parameters and the mining-geological and mining-technical operating conditions of the extraction areas:

$$a_p = \frac{1}{-2.64 \cdot 10^{-4} \cdot m + 1.54 \cdot 10^{-3}}, R = 0.88 \tag{6}$$

$$b_p = \frac{1}{-0.14 \cdot \dfrac{v_{ox}}{H} + 19}, R = 0.88 \tag{7}$$

$$c_p = 0.205 + 0.0148 \cdot \ln(\frac{1}{m \cdot L_l \cdot H}), R = 0.99 \tag{8}$$

where L_l is the lava length.

In addition to equation (5), dependencies were proposed [7] to determine the coordinates of the characteristic points of the earth's surface displacement (figure 1) using the coefficients a_p, b_p, c_p. The coordinates of point A (the beginning of the earth's surface displacement) in front of the stope, respectively, along the abscissa and ordinate axes:

$$x = \frac{4.595 - \ln b}{-c}, y = 0 \tag{9}$$

Similarly, for other characteristic points:

Point O (origin)

$$x = 0, y = \frac{\eta_k}{1 + b} \tag{10}$$

Point B (the beginning of the active stage of the earth's surface displacement)

$$x = \frac{\ln(3.73/b)}{-c}, y = 0.21 \cdot \eta_k \tag{11}$$

Point C (maximum settling rate and curve inflection)

$$x = \frac{\ln b}{c}, y = 0.5 \cdot \eta_k \tag{12}$$

Point D (completion of the active stage and the beginning of the attenuation of the displacement processes)

$$x = \frac{\ln 0.268/b}{-c}, y = 0.79 \cdot \eta_k \tag{13}$$

Point F (beginning of the residual influence of the side job)

$$x = \frac{3.892 \;\; - - \ln b}{c}, y = \frac{0.97}{0.99} \cdot \eta_k \tag{14}$$

In the scheme under consideration (figure 1), the decay stage is limited by the point F. Her settling η_0 is approximately 0.97÷0.99 of the final value η at the end of rock compaction processes [9].

Approximate values of the duration of the active stage of the earth's surface displacement are given in the regulatory documents [5, 6] depending on the depth of the mining operation (H) and the speed of advance of the mining faces. According to mathematical models [9–11], the characteristic features of the processes of displacement of rocks and the earth's surface are also considered in time. This approach does not allow, in the general case, to link the process of displacement of the earth's surface with the development of clearing operations in the excavation area. For this reason, in the general scheme (figure 1), instead of time along the abscissa, we considered the distance L_{ox} from the projection of the stope lines onto the earth's surface to the observation points. Using the method [9] with the use of derivatives, the coordinates of the characteristic points were determined from the extrema of the obtained dependences (equations 9 – 14). The coefficients (a_p, b_p, c_p and a_ox, b_ox, c_ox) of equations 1 and 5 are determined by the most reliable least squares method. For a separate excavation area, when using these coefficients, dependencies 1 and 5 are inherently are functional.

The initial data for calculating the coefficients according to equations 2, 3, 4 and 6, 7, 8 are calculated using the known values of m, H, v_{ox} and m, H, v_{ox}, L respectively. This greatly simplifies the necessary calculations of the parameters of the displacement of the earth's surface troughs, but these dependencies are not functional.

If we prove the closeness of the results obtained by the least squares method, and using empirical equations established on the basis of correlation analysis, then with high reliability it is possible to predict the processes of displacement of undermined rocks and the parameters of the trough displacement of the earth's surface. In this case, there is no need to simultaneously conduct long-term and labor-intensive observations, both on the earth's surface and in mine workings.

2. Purpose, idea and research methodology

2.1. The goal of the research

Given the state of the issue under consideration, the purpose of this work is:

- on the basis of theoretical assumptions and experimental data, to establish a logical relationship between the parameters of the shear half-trough above the cut working and above the stope at its sufficient distance from the cut furnace;

Table 1. The results of determining the coefficients of equation 1 by the least squares method (a_p^k, b_p^k, c_p^k)and based on their correlation dependences (2, 3, 4) on mining-geological and mining engineering factors (a_p^a, b_p^a, c_p^a).

Mine, reservoir, lava, literary source	Operating conditions of excavation sites					The coefficients of equation (1) calculated by the least squares method			Calculation coefficients according to equations (2, 3, 4)		
	Post processing direction	m, m	H, m	L, m	v, m/mon	a_p^k	b_p^k	c_p^k	a_p^a	b_p^a	c_p^a
'Stepnaya', C_6, No. 604, [18]	By rebellion	0.91	106	150	57	853	1550	-0.026	910*	1620	-0.026
'Anniversary', $C_6^{'}$, No. 530, [9]	Along strike	1.00	150	206	20	927	1520	-0.014	867	1330	-0.017

*note – accepted, $a_p^a = m$, according to the empirical equation (2) $a_p^a = 1009mm$, which is greater than the value of $m = 910mm$

- to consider the convergence of the results between the parameters of the trough of the earth's surface displacement, determined respectively on the basis of the least squares method and the method based on correlation dependencies on mining-geological and mining-technical conditions for mining operations.

2.2. The idea

The idea of the work is to determine the dependencies obtained on the basis of experimental data for a separate excavation area and processed by the least squares method, and compare them with the dependencies established by the general results of the correlation analysis for different mining, geological and mining conditions.

Table 2. The results of determining the coefficients of equation 5 by the least squares method ($a^k_{ox}, c^k_{ox}, c^k_{ox}$) and on the basis of correlation dependences (6, 7, 8) on mining-geological and mining-technical factors.

Mine, reservoir, lava, literary source	The coefficients of equation (5) calculated by the least squares method			Coefficients calculated according to equations 6, 7, 8		
	a^k_{ox}	b^k_{ox}	c^k_{ox}	a^k_{ox}	b^a_{ox}	c^a_{ox}
'Stepnaya', C_6, No. 604, [18]	832	5.8	0.064	764	8.7	0.063
'Anniversary', $C_6^{‘}$, No. 530, [9]	915	12.5	0.050	783	5.3	0.052

Table 3. Estimated values of the coordinates ($\eta_o x, L_o x$) of the characteristic points of the curve of subsidence of the earth's surface above the stope when processing the 604th lava of the formation C_6 Stepnaya mine.

Characteristic points of the curve	Coordinates of characteristic points according to equations 9-14				Subsidence of the earth's surface according to equation (5) for different methods of determining empirical coefficients $a_o x, b_o x, c_o x$		Average distances from points to the projection of the production face along the abscissa axis [19], $L_o x, m$		
	Determination of empirical coefficients by the method of least squares		Empirical coefficients are determined by a method based on correlation analysis						
	L^{1k}_{ox}, m	η^{1k}_{ox}, mm	L^a_{ox}, m	η^a_{ox}, mm	η^k_{ox}, mm	η^a_{ox}, mm	Empirical Equations	r	L_{ox}, m
A	-44	0	-39	0	8	5	$L_A = -0.264H$	-0.96	-28
O	0	122	0	79	122	79	-	-	0
B	7	175	13	161	177	159	$L_B = 0.107H$	0.92	11
C	27	416	34	385	410	380	$L_C = 0.290H$	0.98	31
D	48	657	55	608	656	605	$L_D = 0.466H$	0.99	49
F	88	815	96	754	815	754	$L_F = 0.862H$	0.99	91

2.3. Methodology
The methodology is based on the use of experimental data obtained during the operation of a separate extraction area, respectively, at the first stage when the stope is removed from the split furnace and at the second stage above the stope with its sufficient distance from the open cut. This makes it possible to obtain all the necessary experimental data for constructing a general scheme (figure 1) for the development of stope work (removal of the stope from the split furnace) and the formation of a trough of earth surface displacement in two stages. The necessary amount of experimental observations to achieve the goals was carried out at the Stepnaya mine when the seam was mined with longwall No. 604 [17] and at the Yubileynaya mine when the seam was mined with longwall No. 530 [8].

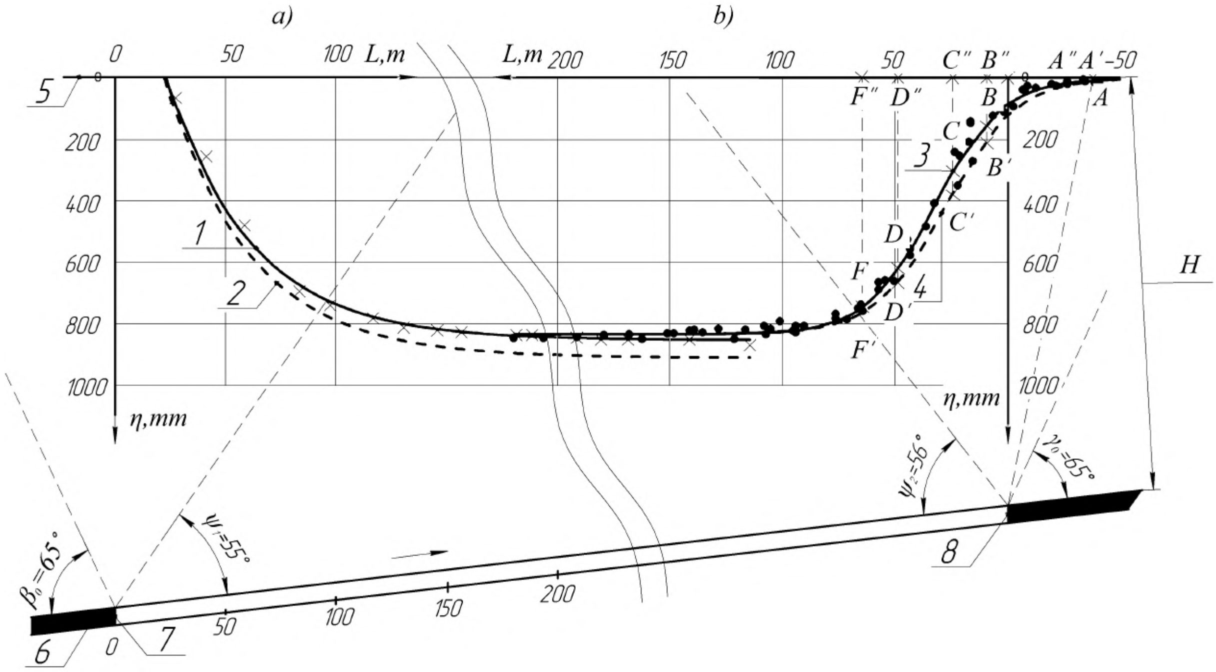


Figure 2. Dependence of the change in the parameters of the displacement trough on the earth's surface with distance from the stope of Chapter No. 604 (Stepnaya mine) on the open working (a) and above the stope (b): 1, 2 – curves of the trajectory of the maximum subsidence of points when the working face is removed from the split furnace, calculated respectively by the least squares method and according to the results of the correlation analysis; 3, 4 – curves of subsidence of points on the earth's surface above the stope, respectively, calculated by the least squares method and according to the results of correlation analysis (they coincide on the graph); η – subsidence of the earth's surface; H – depth of cleaning operations; *A, B, C, D, F* – the position of the characteristic points calculated according to equations (9-14) using the coefficients a, b, c; A', B', C', D', F' – positions of characteristic points calculated according to equation (9-14) using coefficients a_a, b_a, c_a; A'', B'', C'', D'', F'' – the position of the abscissas of the characteristic points of subsidence of the earth's surface according to their dependence on the depth of the clearing operations [19]; 5, 6 – respectively, the earth's surface and the reservoir being developed; 7 – surface of the coal massif of the open cut; 8 – conditional position of the stope in relation to the reference points R25, K30, R35, R40 and R45 as it moves [17]. ψ_1, ψ_2 – angles of total displacements [6]; β_0, γ_0 – boundary angles [6]; + – direction of advance of the stope; •, × – experimental data, respectively, of the maximum subsidence of points on the earth's surface above the cut working and subsidence above the stope [17].

According to the general design scheme, the influence of stopes on the earth's surface (figure 1) was calculated in two ways using the equation of curves for the maximum subsidence of points on the earth's surface. In the first case, the coefficients of equation (1) are determined from the experimental data [17] and [8] by the least squares method (a_p^k, b_p^k, c_p^k). In the second, using the operating conditions of the excavation sites (m, H, v_{ox}), according to equations (2, 3, 4), the empirical coefficients (a_p^a, b_p^a, c_p^a) equations 1, respectively) were calculated.

3. The research results

When determining the empirical coefficient calculated according to equation (2), it is necessary to take into account the value of the reservoir thickness m. The relation $\leq m$ must always hold between them a_p^a. If according to the calculations received $a_p^a > m$, then its value is taken equal to the thickness of the developed reservoir.

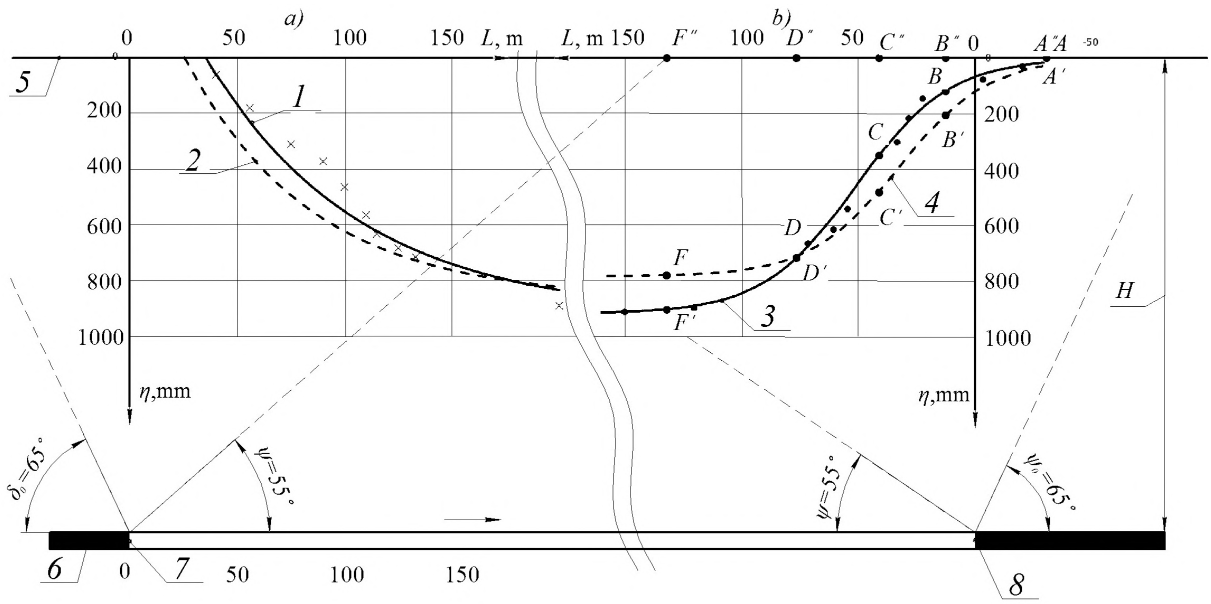


Figure 3. Dependence of the change in the parameters of the trough of the earth's surface displacement as the stope of longwall No. 530 (Yubileynaya mine) is removed from the cut working (a) and above the stope (b): 1, 2 – curves of the trajectory of the maximum subsidence of points when the stope is removed from the split furnace, calculated respectively by the least squares method and according to the results of the correlation analysis; 3, 4 – curves of subsidence of points of the earth's surface above the stope, respectively, calculated by the least squares method and according to the results of the correlation analysis; 5, 6 – respectively, the earth's surface and the reservoir being developed; 7 – surface of the coal massif of the open cut; 8 – conditional position of the stope as it moves relative to points on the earth's surface [8]; η – subsidence of the earth's surface; H – depth of cleaning operations; A, B, C, D, F – the position of the characteristic points calculated according to equations (9-14) using the coefficients a_k, b_k, c_k; A', B', C', D', F' – positions of characteristic points calculated according to equations (9-14) using the coefficients a_k, b_k, c_k; A'', B'', C'', D'', F'' – the position of the abscissas of the characteristic points of subsidence of the earth's surface according to their dependence on the depth of the clearing operations [19]; ψ – angle of full movements [6]; δ_a – boundary angle; $\longrightarrow$ – direction of advance of the stope; $\bullet$, $\times$ – experimental data, respectively, the maximum subsidence of points on the earth's surface above the cut working and subsidence above the stope [8].

It was also established that when the stope advance rate is less than 50 m/month, the value of the empirical coefficient b_p^a is approximately equal to 1330. Similarly, according to equations (2, 3, 4), the empirical coefficients a_p^a, b_p^a, c_p^a were calculated for the operating conditions of longwall No. 530 $C_6^{'}$ of the Yubileynaya mine seam (table 1).

The coefficients of equation (5) were also determined in two ways – by the least squares method and using dependencies (6, 7, 8) obtained from the results of correlation analysis (table 2).

Having determined the empirical coefficients in two ways ($a_{ox}^k, c_{ox}^k, c_{ox}^k$ and $a_{ox}^a, c_{ox}^a, c_{ox}^a$)we calculated, using equations (9-14), the coordinates of the characteristic points of subsidence of the earth's surface above the stopes of the considered longwalls (table 3 and table 4). In addition to these data indicated in the tables, there are also the average values of the characteristic points abscissas. They are calculated depending on the depth of the mining operations according to the method [19], which combines the exponential, hyperbolic tangent and logistic equations recommended respectively [7, 9–11], to describe the curve of subsidence of points on the earth's surface above the moving stope.

On the basis of experimental data [17] and empirical coefficients, graphs of possible changes in the trajectories of maximum subsidence of points were plotted when the longwall of longwall No. 604 of the Stepnaya mine was removed from the open cut and subsidence of points on the earth's surface above the stope (figure 2).

To assess the convergence of the results, we analyzed the relationship between the coordinates of the characteristic points of subsidence of the earth's surface above the production faces,

Table 4. Estimated values of the coordinates ($\eta_o x, L_o x$) of the characteristic points of the earth surface subsidence curve above the stope when processing the 530th lava of the seam $C_6^{'}$, Yubileynaya mine.

Characteristic points of the curve	Coordinates of characteristic points according to equations 9-14				Subsidence of the earth's surface according to equation (5) for different methods of determining empirical coefficients $a_o x, b_o x, c_o x$		Average distances from points to the projection of the production face along the abscissa axis [19], $L_o x, m$		
	Determination of empirical coefficients by the method of least squares		Empirical coefficients are determined by a method based on correlation analysis						
	L_{ox}^{1k}, m	η_{ox}^{1k}, mm	L_{ox}^{a}, m	η_{ox}^{a}, mm	η_{ox}^{k}, mm	η_{ox}^{a}, mm	Empirical Equations	r	L_{ox}, m
A	-41	0	-56	0	9	8	$L_A = -0.264H$	-0.96	-40
O	0	68	0	124	68	124	-	-	0
B	24	192	7	164	192	167	$L_B = 0.107H$	0.92	16
C	51	458	32	392	463	391	$L_C = 0.290H$	0.98	44
D	77	723	57	619	723	615	$L_D = 0.466H$	0.99	70
F	128	897	107	767	896	767	$L_F = 0.862H$	0.99	129

determined in different ways (table 3 and table 4).

The most reliable are the results obtained on the basis of experimental data and their processing by the least squares method.

These results include the coordinates of the characteristic points of subsidence of the earth's surface above the stope when they are calculated according to equations 9-14 using the empirical coefficients of equation 5 calculated by the least squares method ($L_{ox}^{1k}, \eta_{ox}^{1k}$). For this case, the determination of the coordinates of the characteristic points (*A, B, C, D, F*) used the original equation 5 and its derivatives. For this reason, a practical coincidence of the results of determination with (table 3 and table 4) was obtained. Values close to them were also obtained using the results of correlation analysis (figure 4a), as evidenced by the close location of the bisector of the coordinate grid (1) and the averaging line (2).

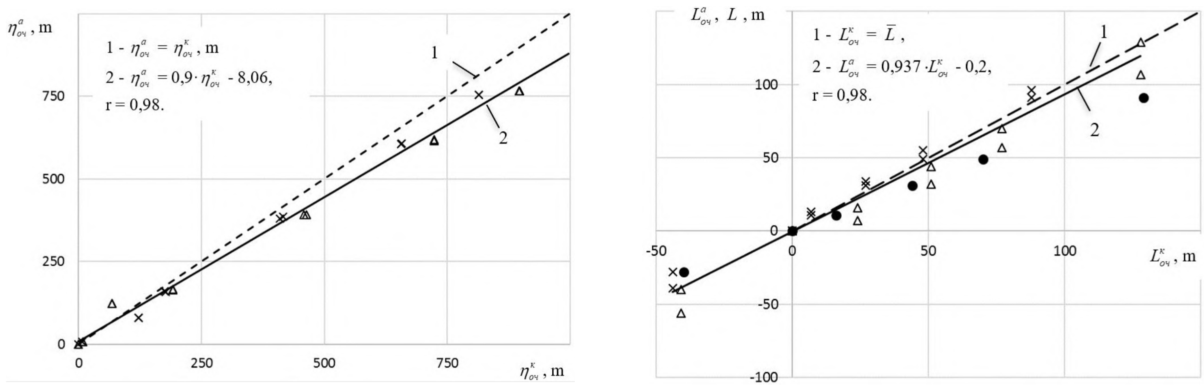
Similar results were obtained when determining the values of the coordinates of characteristic points along the abscissa axis (figure 4b). The values L_{ox}^{1k} are near the bisector of the coordinate grid (1), as is the averaging straight line (2).

Close to the coordinates along the abscissa axis (L_{ox}^{1k}) are and their average values (L_{ox}) calculated [19] depending on the depth of treatment (table 3 and table 4).

4. Conclusions

The conducted research allowed to draw the following conclusions:

- the maximum subsidence of the earth's surface from the side of the split furnace at a



(*a*) (*b*)

Figure 4. (*a*) – along the ordinate axis (subsidence of the earth's surface at the corresponding points); (*b*) – along the abscissa axis (distance from the projection of production faces to the considered points); 1 – bisectors of coordinate grids; $L_{ox}^{1k}, \eta_{ox}^{1k}$ – coordinates established according to equations (9-14), for which the empirical coordinates are calculated by the least squares method according to equation 5; $L_{ox}^{1a}, \eta_{ox}^{1a}$ – coordinates set according to equations (9-14), for which empirical coefficients are calculated using correlation analysis and equation 6-8; L_{ox} – certain distances from the characteristic points to the projection of the stope [19]; $\eta_{ox}^{k}, \eta_{ox}^{a}$ – subsidence of the earth's surface according to equation 5 and empirical coefficients calculated respectively by the least squares method and on the principles of correlation analysis; $\times, \triangle$ – calculated values respectively for the conditions of mines 'Stepnaya' and 'Yubileynaya'; $\times, \triangle$ – calculated values, $L_o^{1a}x$ – respectively, for the conditions of the Stepnaya and Yubileinaya mines; x, y- calculated values, $\eta_o^{ox}x, \eta_o^{k}x, \eta_o^{a}x$ respectively, for the conditions of the Stepnaya and Yubileinaya mines; • – averaged values for the location of characteristic points depending on the depth of work (table 3 and table 4).

sufficient distance from the cutter furnace coincides with the subsidence above the stope at the stage of attenuation of the processes of displacement of undermined rocks, which gives reason to consider the displacement parameters of the stationary and dynamic semitrough close to each other;

- dependencies established by the methodology using the results of correlation analysis are close in their accuracy to the results obtained by the least squares method, which greatly simplifies engineering calculations and obtaining initial data for their production;
- the averaged abscissas of the characteristic points of subsidence of the earth's surface above the stope are determined quite accurately from empirical dependencies and data on the depth of the stope.

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References

[1] Averin S G 1954 *Movement of rocks in underground mining* (Moscow: Ugletekhizdat)
[2] Averin S G 1954 *Mining works under structures and reservoirs* (Moscow: Ugletekhizdat)
[3] Akimov A G, Zemisev V N and Katsnelson N N 1985 *Movement of rocks during underground mining of coal and shale deposits* (Moscow: Nedra)
[4] Iofis M A and Shmelev A I 1985 *Engineering geomechanics in underground mining* (Moscow: Nedra)
[5] Ministry of the Coal Industry of the USSR 1981 *Rules for the protection of structures and natural objects from the harmful effects of underground mining at coal deposits* (Moscow: Nedra)
[6] Minpalivenergo 2003 GSTU 101.00159226.001-2003 Pravyla pidrobky budivel', sporud i pryrodnyh ob'jektiv pry vydobuvanni vugillja pidzemnym sposobom (NPAON 10.0-1.01-03)
[7] Filatiev M and Filatieva E 2018 *E3S Web of Conferences* **60** 00040
[8] Nazarenko V A and Yoshchenko N V 2011 *Patterns of development of maximum subsidence and slopes of the surface in the displacement trough* (Dnepropetrovsk: NGU)
[9] Gavrilenko Y N 2011 *Ugol Ukrainy* **6** 45–49
[10] Kulibaba S B and Rozhko M D 2011 *UkrNDMI NASU* **9** 173–179
[11] Kulibaba S B, Rozhko M D and Khokhlov B V 2010 *UkrNDMI NASU* **7** 40–54
[12] Antoshchenko N I and Chepurnaya L A 2014 *MakNII* **32** 98–106
[13] Antoshchenko N I and Chepurnaya L A 2014 *Naukovyi Visnik NHU* (4) 5–12 URL http://nvngu.in.ua/index.php/en/component/jdownloads/viewdownload/48/823
[14] Averin G A, Kiryazev P N and Dotsenko O G 2010 *Coal of Ukraine* **10** 34–35
[15] Borzykh E P and Gorovoy E P 1999 *Coal of Ukraine* **9** 26–30
[16] Babenko E V 2009 *Problems girsky vice, DonNTU* **17** 67–93
[17] Larchenko V G 1998 *Bulletin of MANEB* **4** 39–41
[18] Nazarenko V O and Pilipenko P P 2012 *Bulletin of ZhDTU* **1** 126–129
[19] Filatiev M V 2017 *Science Bulletin of NSU* **1** 33–37

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Determination of the bearing capacity of biaxially bended beams based on the design strength of reinforced concrete

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Determination of the bearing capacity of biaxially bended beams based on the design strength of reinforced concrete

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Abstract. Based on the design assumptions according to Eurocode 2, the concept of determining the value of the design strength of reinforced concrete has been developed for calculating the bearing capacity of reinforced concrete members subjected to biaxial bending. The theorem on the parallelism of the planes of internal and external forces action is applied. The considered design cases are for the most expected forms of the compressed concrete areas, which are characteristic for biaxial bending of beam members. The value of the coefficient of influence of biaxial bending on the characteristics of the member of rectangular section with triangular and trapezoidal forms of the compressed concrete area is obtained. A methodology for calculating the bearing capacity of biaxially bended members based on the application of the design strength of reinforced concrete is brought to the engineering level of application. An example of a calculation is presented, which demonstrates the convenience and effectiveness of the developed method. The proposed method of calculating the bearing capacity of beam member under biaxial bending is approved by comparing the results of calculations with experimental data for 12 samples of biaxially bended beams.

1. Introduction

Complex deformation of reinforced concrete members is widespread in the practice of operation of many building structures. Wherein, it may be caused by both force and random factors of a constructive, technological or operational nature. As a rule, the main attention of scientists is devoted to the study of reinforced concrete members subjected to axial load and biaxial bending. Proposals were developed for the construction of universal diagrams for determination the bearing capacity of columns under biaxial bending [1–5], while not always acceptable simplifications were used.

Meanwhile, many bending members that are operated in the absence of axial force are subjected to complex deformation. Biaxial bending is exposed by individual members, for example, reinforced concrete girders, crane beams, horizontal elements of frameworks, elements of shells, bridges, staircases and underground structures, crossbars of transport galleries and overpasses, foundation and framing beams, wall panels, etc. and entire spatial systems of buildings and structures.

The application of numerical methods for calculating the bearing capacity of biaxially bended members is considered in works [6–15] for cross-sections of arbitrary shape with different

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arrangement of reinforcement. The diagrams for strength estimation were presented in the form of moment-curvature curves, ultimate strength interaction curves, and three-dimensional fracture surfaces [16].

The results of studies of the strength of biaxially bended reinforced concrete members are given in publications [17, 18]. The developed strength calculation algorithms and their results are compared with experimental data.

The concept of the design strength of reinforced concrete and its application are given in the work [19] for calculating the bearing capacity of members subjected to plane bending. The essence of the considered approach is that reinforced concrete is considered as a composite that has a certain strength characteristic – the design strength of reinforced concrete. At the same time, the strength problems for reinforced concrete members are solved on the basis of the classical theory of resistance of materials. The implemented characteristic is an integral value that takes into account the strength characteristics of concrete and reinforcement, the amount of reinforcement in the section and its location.

It is obvious that it can be used for any type of deformation of a reinforced concrete member, in particular for biaxial bending. The problem of this implementation is complicated by an additional unknown parameter, namely the angle of inclination of the neutral axis, as well as the presence of different forms of the compressed concrete area in the cross-section of the member. To date, no practical proposals have been developed regarding the application of the theory of design reinforced concrete strength for biaxially bended members in this aspect.

2. Results

Obtaining the design strength of reinforced concrete in biaxial bending is considered for members of rectangular section with single reinforcement. At the same time, the assumptions for design according to Eurocode 2 [20] are used. In particular, a rectangular stress distribution in the concrete of the compressed area is accepted, the stress-strain diagram of the reinforcing steel with a physical yield point is assumed to be bilinear with a horizontal section of unlimited length. The deformation criterion is used as a failure criterion.

In general, it is proposed to solve strength problems using the design strength of reinforced concrete on the basis of the dependence

$$M_{Ed} \leq M_{Rd} = f_{zM} W \gamma, \tag{1}$$

where f_{zM} is the design strength of a reinforced concrete member of rectangular section with single reinforcement in plane bending; $W = bd^2/6$ – moment of resistance of a rectangular section; γ is a reducing coefficient for the design strength of a reinforced concrete at biaxial bending.

On the basis of the work [19], the design strength of reinforced concrete for a rectangular section, taking into account the accepted assumptions, is obtained in the form

$$f_{zM} = 6 f_{yd} \rho_l \left(1 - \frac{f_{yd} \rho_l}{2 f_{cd}}\right), \tag{2}$$

where ρ_l is the longitudinal reinforcement ratio.

Using dependence (2), it is possible to tabulate the design strength of reinforced concrete for different classes of concrete and reinforcement at different of reinforcement ratios. For example, table 1 shows the value of f_{zM} for reinforcement of A500C class. It should be noted that the values in table 1 are determined under the condition that at the moment of failure, the stresses in the tensile reinforcement reach the yield point.

To determine the coefficient γ, which takes into account the decreasing of the design strength of reinforced concrete of biaxially bended members, it is first considered the case of biaxial

Table 1. Design values of reinforced concrete strength for bending members of rectangular section with single A500C reinforcement ($f_{yd} = 435$ MPa).

ρ_l, %	C16/20	C20/25	C25/30	C30/35	C32/40	C35/45	C40/50	C45/55	C50/60
0.05	1.29	1.30	1.30	1.30	1.30	1.30	1.30	1.30	1.30
0.50	11.82	12.07	12.22	12.32	12.40	12.48	12.53	12.58	12.62
1.00	21.16	22.19	22.76	23.19	23.52	23.83	24.04	24.21	24.38
1.25	24.91	26.51	27.41	28.08	28.59	29.08	29.40	29.67	29.94
1.75	30.56	33.69	35.45	36.76	37.77	38.72	39.35	39.88	40.41
2.00	–	36.54	38.84	40.56	41.88	43.12	43.94	44.63	45.32
2.50	–	–	44.38	47.06	49.12	51.06	52.35	53.42	54.50
3.00	–	–	–	52.10	55.08	57.86	59.72	61.27	62.82

bending of a reinforced concrete beam, in which the compressed concrete area has the form of a trapezoid. According to the accepted prerequisites, the design scheme of the section has the form presented in figure 1.

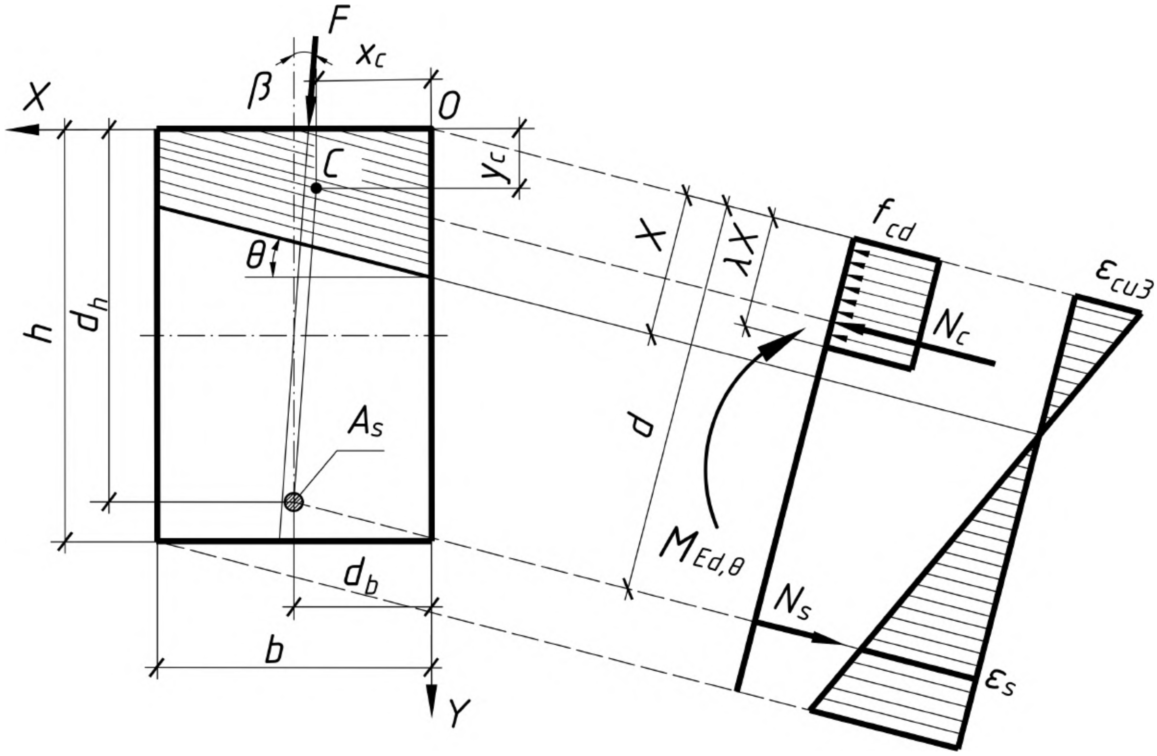

Figure 1. Design diagram of the cross-section of a biaxially bended member with a trapezoidal form of a compressed concrete area.

Taking into account the assumptions outlined above and figure 1, the design equations of equilibrium in the plane of the vertical coordinate axis Y are written in the form:

$$\sum Z = N_s - N_c = 0; \tag{3}$$

$$\sum M_C = M_{Rd,Y} - M_{Ed,Y} = 0, \tag{4}$$

where

$$M_{Rd,Y} = N_s\left(d_h - y_c\right), \tag{5}$$

N_s, N_c – resultant forces, in the reinforcement and in the compressed concrete area, respectively; d_h is the distance from the most compressed concrete fiber of the section to the point of application of the resultant N_s; y_c is the coordinate of application of the resultant N_c; $M_{Rd,Y}, M_{Ed,Y}$ – values of bending moments from the action of internal and external forces, respectively, in the plane of the coordinate axis Y at the moment of exhaustion of the strength of the reinforced concrete member in the normal section.

To obtain the necessary design formulas, the expressions of the resultant N_c, as well as the distance y_c from the most compressed concrete fiber to the point of application of N_c, were first realized. The desired expressions for the trapezoidal form of the compressed concrete area (figure 1) are obtained in the following form:

$$N_c = \frac{f_{cd}b}{\cos\theta}\left(\lambda X - \frac{b\sin\theta}{2}\right), \tag{6}$$

$$y_c = \frac{3\lambda^2X^2 - 3\lambda Xb\sin\theta + b^2\sin^2\theta}{3\cos\theta\left(2\lambda X - b\sin\theta\right)}, \tag{7}$$

where θ is the angle of inclination of the neutral axis; X is the neutral axis depth.

Since the problem is solved for the case when the stresses in the reinforcement of the tensile area reach the values $\sigma_s = f_{yd}$, then the resultant force in the tensile reinforcement is determined by the dependence

$$N_s = f_{yd}A_s. \tag{8}$$

After substituting (6) – (7) in (3) and (5) for the trapezoidal form of the compressed area, the formulas for determining the neutral axis depth X and the ultimate value of the moment $M_{Rd,Y}$ in the plane of the coordinate axis Y are obtained:

$$X = \frac{f_{yd}A_s\cos\theta}{f_{cd}\lambda b} + \frac{b\sin\theta}{2\lambda}, \tag{9}$$

$$M_{Rd,Y} = f_{yd}A_s\left(d_h - \frac{3\lambda^2X^2 - 3\lambda Xb\sin\theta + b^2\sin^2\theta}{3\cos\theta\left(2\lambda X - b\sin\theta\right)}\right). \tag{10}$$

Substituting the value of X from equation (9) into equation (10) and making the substitution $\rho_l = A_s/(bd_h)$, it is obtained

$$M_{Rd,Y} = f_{yd}\rho_l bd_h\left(d_h - \frac{f_{yd}\rho_l d_h}{2f_{cd}} + \frac{f_{cd}b^2tan^2\theta}{24f_{yd}\rho_l d_h}\right). \tag{11}$$

By equating the right-hand side of inequality (1) and equation (9) taking into account (2), it is possible to obtain the coefficient of reduction of the design strength of reinforced concrete at biaxial bending for a rectangular cross-section with a trapezoidal form of the compressed concrete area

$$\gamma = 1 - \frac{f_{cd}^2\tan^2\theta}{12f_{yd}\rho_l\left(2f_{cd} - f_{yd}\rho_l\right)}\left(\frac{b^2}{d_h^2}\right). \tag{12}$$

To obtain the dependence $\theta = f(\beta)$, which can be used to calculate the angle θ of inclination of the neutral axis, the condition of parallelism of the planes of the internal $M_{Rd,\beta}$ and external $M_{Ed,\beta}$ bending moments action is applied. Those planes are inclined at an angle β to the vertical

Y axis of symmetry of the section. According to this condition in the XOY coordinate system (figure 1) the ratio is valid

$$\tan\beta = \frac{d_b - x_c}{d_h - y_c}, \tag{13}$$

where d_b, d_h are the effective heights, respectively, in the direction of the X and Y axes of the cross-section of the biaxially bended member; x_c, y_c are the coordinates of the point of application of the resultant in the compressed concrete area in XOY coordinate system. The coordinate y_c is determined by dependence (7), and the coordinate x_c is determined by the following dependence

$$x_c = \frac{b\,(3\lambda X - 2b\sin\theta)}{3\,(2\lambda X - b\sin\theta)}. \tag{14}$$

After substituting (9) into (7) and (14), it is obtained that the formulas for calculating the coordinates of the application of resultant force in the compressed area take the form

$$x_c = \frac{b}{2} - \frac{f_{cd} b^3 \tan\theta}{12 f_{yd} A_s}, \tag{15}$$

$$y_c = \frac{f_{yd} A_s}{2 f_{cd} b} + \frac{f_{cd} b^3 \tan^2\theta}{24 f_{yd} A_s}. \tag{16}$$

Substituting (15) and (16) into the original formula (13) makes it possible to obtain an equation whose solution with respect to $\tan\theta$ will be a formula that allows calculating the angle θ depending on the angle β of inclination of the external load plane

$$\tan\theta = -\cot\beta + \sqrt{\cot^2\beta - \frac{24 t f_{yd} A_s \cot\beta}{f_{cd} b^3}}, \tag{17}$$

where $t = d_b - d_h \tan\beta + \frac{f_{yd} A_s \tan\beta}{2 f_{cd} b} - \frac{b}{2}$.

Having singled out the ratio b/d_h as one that can be specified, and performing the substitution ρ_l, the formula for determining the angle θ is written in the form

$$\tan\theta = -\cot\beta + \sqrt{\cot^2\beta - \frac{24 f_{yd}\rho_l \cot\beta}{f_{cd}} \left(\left(k - \frac{1}{2}\right)\frac{b}{d_h} - \tan\beta\left(1 - \frac{f_{yd}\rho_l}{2 f_{cd}}\right)\right)\left(\frac{d_h}{b}\right)^2}, \tag{18}$$

where $k = d_b/b$.

Thus, using dependencies (12) and (18), it is possible to tabulate the coefficient of decreasing of the strength of reinforced concrete at biaxial bending when the angle β of the external load plane inclination to the vertical axis of symmetry of the section is changed for a certain value of the b/d_h ratio.

In a similar way, the dependencies for the triangular form of the compressed concrete area are found. In this case the design scheme is shown in figure 2.

The general equilibrium equations for the considered design diagram (figure 2) will have the form (3) – (4).

The sought expressions of the resultant N_c in (3), as well as the coordinates y_c of its application in (4) for the triangular form of the compressed concrete area (figure 2) take the following form:

$$N_c = \frac{f_{cd}\lambda^2 X^2}{\sin 2\theta}, \tag{19}$$

$$y_c = \frac{\lambda X}{3\cos\theta}. \tag{20}$$

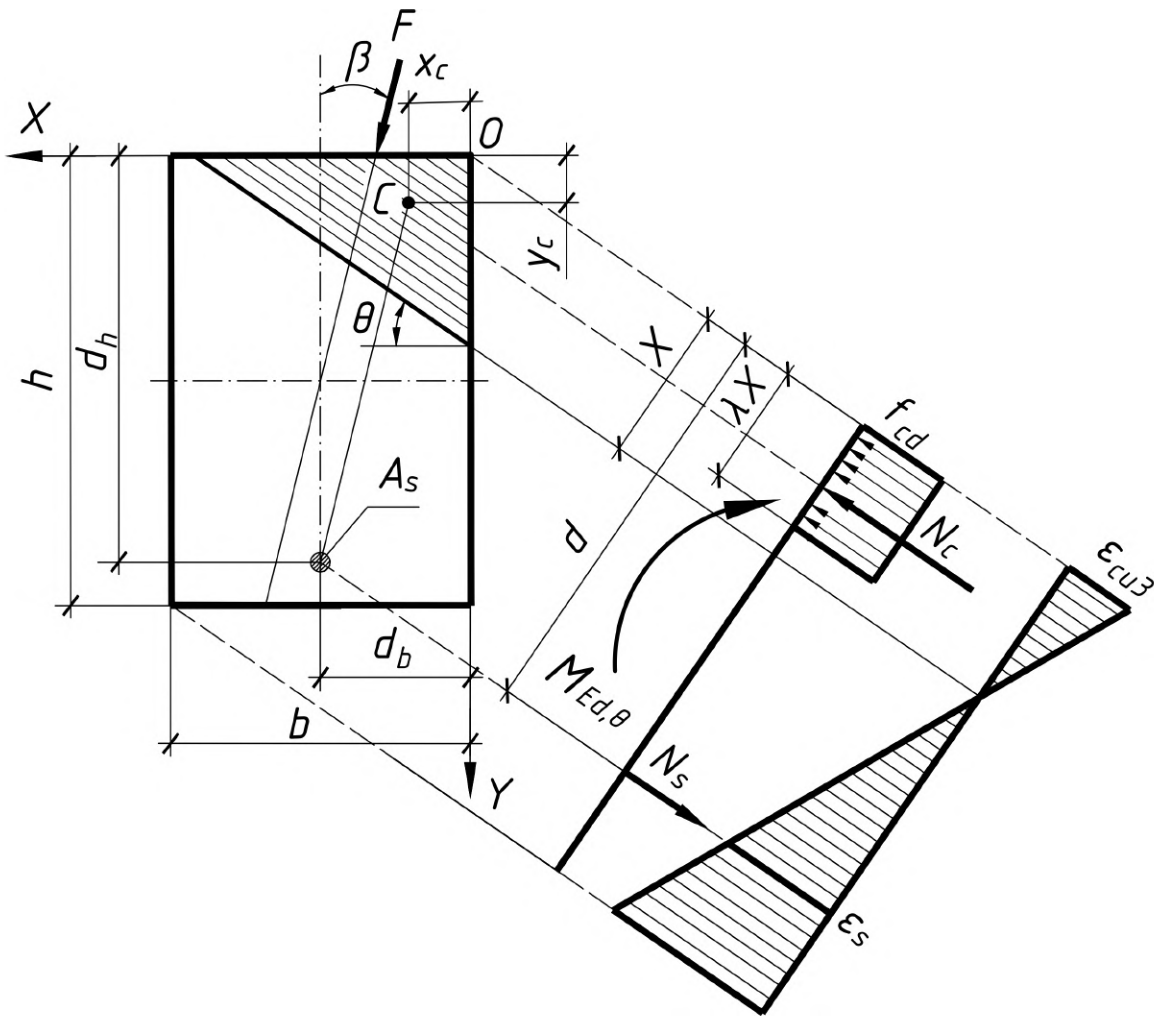

Figure 2. Design diagram of the cross-section of a biaxially bended member with a triangular form of a compressed concrete area.

Since the problem is solved for the case when the stresses in the reinforcing steel of the tensile area reach the values $\sigma_s = f_{yd}$, the resultant force in the tensile reinforcement is determined by dependence (8).

After substituting (19) – (20) in (3) and (5) for the triangular form of the compressed area, the formulas for determining the neutral axis depth X and the ultimate value of the moment $M_{Rd,Y}$ in the plane of the coordinate axis Y are obtained:

$$X = \sqrt{\frac{f_{yd} A_s \sin 2\theta}{f_{cd} \lambda^2}}, \tag{21}$$

$$M_{Rd,Y} = f_{yd} A_s \left(d_h - \frac{\lambda X}{3 \cos \theta} \right). \tag{22}$$

By substituting the value of X from equation (21) into equation (22) and performing the substitution ρ_l, it is obtained

$$M_{Rd,Y} = f_{yd} \rho_l b d_h \left(d_h - \frac{1}{3} \sqrt{\frac{2 f_{yd} \rho_l b d_h \tan \theta}{f_{cd}}} \right). \tag{23}$$

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By equating the right-hand side of inequality (1) and equation (23) taking into account (2), an expression for calculating the coefficient γ is obtained, which takes into account the influence of biaxial bending on the values of the member characteristics in (1) for a rectangular cross-section with a triangular form of a compressed concrete area

$$\gamma = \frac{2f_{cd}}{2f_{cd} - f_{yd}\rho_l} - \sqrt{\frac{8f_{cd}f_{yd}\rho_l \tan\theta}{9(2f_{cd} - f_{yd}\rho_l)^2}\frac{b}{d_h}}. \tag{24}$$

To obtain the dependence $\theta = f(\beta)$, condition (13) is applied, in which the coordinate y_c is determined by dependence (20), and the coordinate x_c is determined by the following dependence

$$x_c = \frac{\lambda X}{3\sin\theta}. \tag{25}$$

After substituting (21) into (20) and (25), it is obtained that the formulas for calculating the coordinates of the application of resultant force N_c in the compressed area take the form:

$$x_c = \frac{1}{3}\sqrt{\frac{2f_{yd}A_s}{f_{cd}\tan\theta}}, \tag{26}$$

$$y_c = \frac{1}{3}\sqrt{\frac{2f_{yd}A_s}{f_{cd}}\tan\theta}. \tag{27}$$

Substituting (26) and (27) into the original formula (13) makes it possible to find an equation whose solution with respect to $\tan\theta$ will be a formula that allows calculating the angle θ depending on the angle β of inclination of the external load plane

$$\tan\theta = \frac{f_{cd}\left(\sqrt{c^2 + 8\frac{f_{yd}A_s}{f_{cd}}\tan\beta} - c\right)^2}{8f_{yd}A_s\tan^2\beta}, \tag{28}$$

where $c = 3d_b - 3d_h\tan\beta$.

Having singled out the ratio b/d_h as one that can be specified, the formula for determining the angle θ is written in the form

$$\tan\theta = \frac{d_h}{b}\frac{f_{cd}l^2}{8f_{yd}\rho_l\tan^2\beta}\left(\sqrt{1 + \frac{8f_{yd}\rho_l}{f_{cd}l^2}\frac{b}{d_h}\tan\beta} - 1\right)^2, \tag{29}$$

where $l = 3kb/d_h 3\tan\beta; k = d_b/b$.

Full calculation of biaxially bended members according to the described method is possible only if the form of the compressed concrete area is known. For its definition, a prerequisite is adopted, on the transformation of the trapezoidal form of the compressed area into a triangular one on the border of the limiting state of its existence. The considered state is characterized by one case of the position of the neutral axis, namely, when the neutral axis crosses the less compressed edge. This position of the neutral axis, as can be seen from the comparison of the design diagrams shown in figure 1 and figure 2, is the boundary between these schemes.

According to the design diagram (figure 2), at the limit position of the neutral axis, the equation (3) using (19) and (8) will have the form

$$\frac{f_{cd}X^2\lambda^2}{\sin 2\theta} = f_{yd}A_s. \tag{30}$$

From the analysis of equation (30), it is obvious that the condition for delimiting the forms of the compressed area will be inequality

$$\frac{f_{cd}X^2\lambda^2}{\sin 2\theta} \geq f_{yd}A_s. \tag{31}$$

If condition (31) is fulfilled, the compressed concrete area has the form of a triangle, if it is not fulfilled, the compressed area has the form of a trapezoid. To use this condition in practice, it is necessary to know all the parameters included in inequality (31). When solving the bearing capacity check problem, two parameters X and θ are unknown.

To determine the unknowns, the condition of the parallelism of the planes of action of internal and external forces is applied, which, based on the design diagram, is written in the form (13).

Substituting (25) and (20) into (13) under the condition that for the limiting case of the position of the neutral axis $\lambda X = b\sin\theta$ it is obtained

$$\frac{\lambda X}{\cos\theta} = 3d_h - (3d_b - b)\cot\beta. \tag{32}$$

After substituting (32) into inequality (31) and performing mathematical transformations, the condition for delimiting the forms of the compressed area is reduced to a simple form

$$\cot\beta \leq \frac{3f_{cd} - 2f_{yd}\rho_l}{f_{cd}\,(3k-1)}\frac{d_h}{b}. \tag{33}$$

Therefore, if inequality (33) is fulfilled, the form of the compressed area of concrete is triangular, if it is not fulfilled, it is trapezoidal.

Using the obtained dependencies (12), (18), (24), (29) and (33), it is possible to determine the coefficient γ of taking into account the influence of biaxial bending on the values of the member characteristics in (1) for a rectangular section depending on the angle of inclination of the external load plane. At the same time, the geometric characteristics of the cross-section in the form of ratios b/d_h and $k = d_b/b$ (figures 1, 2) and the longitudinal reinforcement ratio ρ_l of the cross-section are also taken into account. The values of the coefficient γ for reinforcement of class A500C are given in table 2 for the case of the tensile reinforcement reaching the yield point at the time of member failure.

Using the developed method, the bearing capacity of the biaxially bended beams studied in [18] was determined. The calculation results and experimental data are shown in table 3.

To illustrate the developed calculation method, the following example is considered.

Given: a reinforced concrete beam of a rectangular profile with cross-sectional dimensions $b = 200$ mm, $h = 450$ mm, the beam is made of concrete class C25/30 ($f_{cd} = 17$ MPa); in the beam, tensile reinforcement (4Ø16) with a cross-sectional area of $A_s = 804$ mm^2 of class A500C ($f_{yd} = 435$ MPa) is located symmetrically relative to the vertical axis at a distance of its centre of gravity from the lower face of the cross-section $a = 50$ mm, the angle between the vertical axis of symmetry of the cross-section and the plane of action of the external load $\beta = 5°$. It is necessary to determine the maximum value of the bending moment that the beam may perceive.

Calculation: Determination of the geometric characteristics of the section

$d_h = h - a = 450 - 50 = 400$ mm; $d_b = b/2 = 200/2 = 100$ mm,

$b/d_h = 200/400 = 0.5$; $d_b/b = 100/200 = 0.5$.

Determination of the longitudinal reinforcement ratio

$\rho_l = A_s/(bd_h) \times 100\% = 804/(200 \times 400) \times 100\% = 1\%$.

The design strength of reinforced concrete is determined from table 1 $f_{zM} = 22.76$ MPa.

According to table 2, the coefficient $\gamma = 0.962$.

Modulus of the section is $W = bd_h^2/6 = 200 \times 400^2/6 = 5333333$ mm^3.

Table 2. The coefficient γ of taking into account the influence of biaxial bending on the design strength of reinforced concrete for members of a rectangular section with single reinforcement of class A500C (f_{yd}=435 MPa, ρ_l= 1, b/d_h= 0.5, k= 0.5).

$\beta°$	C16/20	C20/25	C25/30	C30/35	C32/40	C35/45	C40/50	C45/55	C50/60
0	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
1	0.998	0.998	0.998	0.999	0.999	0.999	0.999	0.999	0.999
2	0.991	0.993	0.994	0.994	0.995	0.995	0.996	0.996	0.996
3	0.981	0.984	0.986	0.987	0.989	0.990	0.991	0.991	0.992
4	0.966	0.972	0.975	0.978	0.980	0.982	0.983	0.985	0.986
5	–	0.957	0.962	0.966	0.969	0.972	0.975	0.976	0.978
6	–	0.940	0.947	0.952	0.957	0.961	0.964	0.967	0.969
7	–	0.922	0.930	0.937	0.942	0.948	0.952	0.955	0.959
8	–	0.901	0.911	0.919	0.926	0.933	0.938	0.942	0.946
9	–	–	0.890	0.899	0.907	0.915	0.921	0.926	0.931
10	–	–	0.867	0.878	0.886	0.895	0.902	0.907	0.913
11	–	–	0.843	0.854	0.863	0.873	0.880	0.886	0.892
12	–	–	0.816	0.828	0.838	0.848	0.855	0.861	0.868
13	–	–	–	0.800	0.810	0.820	0.828	0.835	0.842
14	–	–	–	0.772	0.782	0.792	0.799	0.806	0.813

Table 3. Results of comparison of experimental and theoretical values of the destructive bending moment of biaxially bended beams (b/d_h = 0.8; k = 0.62).

Beam code	σ_{ym}, MPa	A_s, mm^2	ρ_l, %	f_{cm}, MPa	$\beta°$	f_{zM}, MPa	γ	M_Y, kNm	$M_{\beta,t}$, kNm	$M_{\beta,e}$, kNm	Δ, %
BR-1-1	379	544	1.7	25	0.00	33.69	0.975	35.03	35.03	34.65	-1.1
BR-1-2	379	544	1.7	25	6.40	33.69	1.000	35.93	35.71	39.60	9.8
BR-1-3	379	544	1.7	25	10.00	33.69	0.991	35.61	35.07	39.15	10.4
BR-1-4	379	544	1.7	25	13.36	33.69	0.969	34.82	33.88	38.25	11.4
BR-1-5	379	544	1.7	22	20.00	33.01	0.892	31.40	29.50	30.15	2.1
BR-3-1	542	292	0.91	22	0.00	26.32	0.979	27.48	27.48	27.90	1.5
BR-3-2	542	292	0.91	22	13.36	26.32	0.971	27.27	26.54	30.15	12.0
BR-3-3	542	292	0.91	22	20.00	26.32	0.905	25.40	23.87	27.45	13.1
BR-4-1	581	462	1.44	21	0.00	40.28	0.958	41.15	41.15	41.40	0.6
BR-4-2	581	462	1.44	21	6.40	40.28	1.000	42.96	42.69	42.30	-0.9
BR-4-3	581	462	1.44	21	10.00	40.28	0.991	42.56	41.91	44.10	5.0
BR-4-4	581	462	1.44	21	13.36	40.28	0.964	41.40	40.28	43.65	7.7

Using formula (1), the bending moment that might be perceived by the beam in the vertical plane is calculated $M_{Rd,Y} = f_{zM}W\gamma = 22.76 \times 5333333 \times 0.962 = 116.77 \times 10^6$ Nmm = =116.77kNm.

The moment in the external load plane action passing at an angle β to the vertical axis of symmetry of the section is $M_{Rd,\beta} = M_{Rd,Y} \cos\beta = 116.77 \times \cos 5° = 116.33$ kNm.

3. Conclusions

The concept of determining the value of the design strength of reinforced concrete for calculating the bearing capacity of reinforced concrete members subjected to biaxial bending has been developed. The value of the coefficient of influence of biaxial bending on the characteristics of the member of rectangular section with triangular and trapezoidal forms of the compressed concrete area is obtained. The methodology is brought to the engineering level of application. The proposed method of calculating the bearing capacity of beam members under biaxial bending ensures a satisfactory convergence of the calculation and experimental data.

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References

[1] Parme A L, Nieves J M and Gouwens A 1966 *ACI Journal Proceedings* **63**(9) 911–24 URL https://doi.org/10.14359/7658
[2] Weber D C 1966 *ACI Journal Proceedings* **63**(11) 1205–30 URL https://doi.org/10.14359/7667
[3] Row D G and Paulay T 1973 *Bulletin of the New Zealand Society for Earthquake Engineering* **6**(3) 110–121 URL https://doi.org/10.5459/bnzsee.6.3.110-121
[4] Virdi K S and Dowling P J 1973 *Proceedings of the Institution of Civil Engineers* **55**(1) 251–272 URL https://doi.org/10.1680/iicep.1973.4958
[5] Hsu C T 1989 *ACI Structural Journal* **86**(4) 460–8 URL https://doi.org/10.14359/2967
[6] Yau C Y, Chan S L and So A K W 1993 *ACI Structural Journal* **90**(3) 269–78 URL https://doi.org/10.14359/4235
[7] Kim J K and Lee S S 2000 *Engineering Structures* **22**(11) 1518–1528 ISSN 0141-0296 URL https://doi.org/10.1016/S0141-0296(99)00090-5
[8] Fafitis A 2001 *Journal of Structural Engineering* **127**(7) 840–6 URL https://doi.org/10.1061/(ASCE)0733-9445(2001)127:7(840)
[9] Sfakianakis M G 2002 *Advances in Engineering Software* **33**(4) 227–42 URL https://doi.org/10.1016/S0965-9978(02)00002-9
[10] Furlong R W, Hsu C T T and Mirza S A 2004 *ACI Structural Journal* **101**(3) 413–23 URL https://doi.org/10.14359/13101
[11] Bonet J L, Romero M L, Miguela P F and Fernandez M A 2004 *Computers & Structures* **82**(2-3) 213–25 URL https://doi.org/10.1016/j.compstruc.2003.10.009
[12] Bonet J L, Barros M H F M and Romero M L 2006 *Computers & Structures* **84**(31-32) 2184–93 URL https://doi.org/10.1016/j.compstruc.2006.08.065
[13] Pallarés L, Bonet J L, Miguel P F and Fernández Prada M A 2008 *Engineering Structures* **30**(7) 1879–94 URL https://doi.org/10.1016/j.engstruct.2007.12.005
[14] Chang S Y 2010 *Journal of Structural Engineering* **136**(1) 12–25 URL https://doi.org/10.1061/(ASCE)0733-9445(2010)136:1(12)
[15] Di Ludovico M, Lignola G P, Prota A and Cosenza E 2010 *ACI Structural Journal* **107**(4) 390–9 URL https://doi.org/10.14359/51663811
[16] Papanikolaou V K 2012 *Computers & Structures* **98-99** 33–54 URL https://doi.org/10.1016/j.compstruc.2012.02.004
[17] Vaz Rodrigues R 2015 *Engineering Structures* **104**(1) 1–17 URL https://doi.org/10.1016/j.engstruct.2015.09.016
[18] Pavlikov A, Kosior-Kazberuk M and Harkava O 2018 *International Journal of Engineering & Technology* **7**(3.2) 299–305 URL https://doi.org/10.14419/ijet.v7i3.2.14423
[19] Pavlikov A, Kochkarov D and Harkava O 2019 Calculation of reinforced concrete members strength by new concept *CONCRETE. Innovations in Materials, Design and Structures : Proceedings of the fib Symposium 2019 held in Kraków, Poland 27-29 May 2019* (Kraków: Krakow University of Technology) pp 820–7 URL http://reposit.nupp.edu.ua/handle/PoltNTU/6064
[20] 2004 *Eurocode 2: Design of concrete structures - Part 1-1: General rules and rules for buildings* (Brussels: European Committee for Standardization) URL https://www.phd.eng.br/wp-content/uploads/2015/12/en.1992.1.1.2004.pdf

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Biotechnical approach for a continuous simultaneous increase of indoor and outdoor air quality

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Abstract. Phytofiltration is the most sustainable way to achieve a better quality of inlet air in buildings in a polluted environment. But they don't take into account the biorhythms of plants and pollute the inlet air with CO_2 during breathing only time. We collected and analysed data about the biorhythms of plants. As a result, a new bi-directional phytofilter was offered for cleaning and oxygenation of the inlet ventilation air, and also to protect the environment by cleaning the exhaust air from different pollutants. The device has spaces with shifted illumination rhythms and a valve system. A controller directs the inlet air to the space(s), where plants release CO_2. The outlet air runs through other spaces. Literature data show that in the less favourable case, the CO_2 and oxygen emissions are balanced per day without overall CO_2 gain to the environment. When plants are growing, they sequestrate CO_2 to catch greenhouse gas emissions. Either natural light, artificial light, or a combination of the two can be used. While the second option simply demands one plant metabolism type, the first option needs a combination of CAM metabolism and other plants

1. Introduction

The fundamental issue with contemporary dense construction and high levels of traffic is their detrimental impact on the environment, which lowers the quality of the outdoor air. Outdoor air in industrial areas or near congested roadways is too filthy to be used for ventilation. The air is passed to an air handling unit, which can remove dust, and change temperature and humidity, but can't effectively eliminate the gas pollutants. Thus, dirty inlet air pollutes the indoor one. The last one is additionally polluted by indoor sources such as furniture, water supply, equipment, finishing materials, etc. And finally, the more polluted indoor air is released into the environment through exhaust ventilation and makes the environment dirtier. To solve the problem, we can use a biotechnological approach – green structures that connect living plants and building structures [1–7]. The most perspective solution for inlet/internal ait treatment is fytofilters with living plants. Modern phytofiltration systems in rooms or ventilation systems run independently on the biorhythms of plants. At the time when plants don't release oxygen, they cause secondary CO_2 pollution.

2. The current state of phytoremediation of indoor air

2.1. Mechanisms of removal of air pollutants by plants

Indoor air pollution can be remedied using methods such as chemical cleaning, assimilation by ventilation, insulation, and plant decontamination (phytoremediation). Plants are autotrophic organisms that perform intensive gas exchange to carry out cellular vital activities, thanks to which air pollutants can be absorbed or accumulated inside [8–10]. The term "Phytoremediation" means bioremediation of polluted air, soil and water with the help of plants [11].

Plants reduce the mobility, toxicity, and volume of pollutants through a variety of mechanisms, such as accumulation, volatilization, and degradation. These biological processes ultimately require light energy (solar, high-efficient LED phytolamps), and therefore phytoremediation is a cheaper method than engineering ones. Phytoremediation is considered an alternative or additional air purification technology [11].

More than 35 years ago, the US National Aeronautics and Space Administration (NASA) faced health problems related to poor indoor air in fully enclosed systems in outer space. More than 300 volatile organic compounds (VOCs) were found in the environment of the spacecraft, which were cause the deterioration of the astronauts' health. To solve this problem, NASA researched the use of plants to remove pollutants and maintain a safe breathing environment. The first studies on the purifying properties of plants were conducted within the framework of NASA's Clean Air project in cooperation with the Association of Landscape Contractors of America (ALCA) [12].

The results of these studies have shown that some common indoor plants in combination with activated carbon as a substrate contribute to the natural purification of the air from several of toxic substances for humans, such as benzene, formaldehyde and trichloroethylene, helping to neutralize the sick building syndrome. The first list of air-purifying plants was formed by NASA and published in 1989 [12–14], which was aimed at research on air purification in the closed conditions of space stations. The plants included in the first list, in addition to the absorption of carbon dioxide and the release of oxygen, also eliminated a significant amount of benzene, formaldehyde and trichloroethylene.

The second and third lists were formed later by Wolverton in the book [15] and article [16]. These works provide information about plants that remove more specific chemicals from the air. NASA researchers suggest that effective air purification can be achieved with at least one plant per 100 square feet (approximately 9.29 square meters) of a home or office space. At the initial stage of research, only plants grown hydroponically (that is, without soil) were considered, in later studies it was shown that microorganisms in a soil mixture in a pot can remove benzene from the air. Certain types of plants also contribute to the removal of benzene. Given the surface area required, using leaves alone was impractical, so the NASA team investigated the possibility of toxin removal by microorganisms in the rhizosphere. In addition, research conducted at NASA's National Space Technology Laboratories has shown that phytoremediation is effective in treating residential wastewater and in removing compounds containing radioactive components from both soil and wastewater [16, 17].

In 1985, fundamental research that revealed the ability of indoor plants and their root microorganisms to clean indoor air from chemical pollutants received further development. However, the removal time of pollutants can be long [18].

There are different forms of plant pollution removal. One of them is absorption of pollutants by roots from soil and water. Root uptake is related to contaminant concentration and properties, plant species/composition, time of exposure, and other system variables. When organic pollutants (such as trichloroethylene) are present in the shoots, they can be transported to the roots by the phloem. The transformation or degradation of the pollutant by plant tissues is another important issue in phytoremediation [19] gaseous pollutants and particles such as dust and bioaerosols are adsorbed on the leaf surface, gaseous pollutants are absorbed by stomata and accumulate in various internal structures, photosynthesis can remove CO_2 and produce O_2. Leaf transpiration and evaporation from the environment for rooting (soil, precipitation, sludge, sewage) [20] increase the moisture content.

2.2. Removal of volatile organic compounds (VOCs) from indoor air by plants

Volatile organic compounds (VOCs)are an important class of indoor air pollutants because they cause a wide range of harmful effects on human health, even at low concentrations. Despite this, currently available techniques for removing VOCs from indoor air are often ineffective, especially when it comes to gaseous compounds [21].

The idea of the removal of volatile organic compounds from indoor air by plants was also presented by Wolverton et al [12] in 1989, as discussed above. These studies confirmed that potted plants can remove significant or large amounts of gaseous VOCs in sealed chambers, reducing VOCs from 10 % to 90 % in 24 h [22].

Wolverton et al studied 12 plants for removing VOCs and demonstrated the possibility of improving indoor air quality by removing traces of organic pollutants from the air in energy-efficient buildings. They showed that contact of the root area with air has a higher efficiency in removing organic pollutants [12, 23].

The work [24] describes the following possible ways of removal of volatile organic compounds by plants:

- removal of the above-ground zone of plants;
- removal of VOCs by microorganisms in the soil;
- removal through the root system;
- removal by the plant environment (substrate).

Highlighting the method of VOC removal by microorganisms in the soil is worthwhile, which is a subspecies of phytoremediation and phytodegradation, which describes the breakdown of complex organic pollutants into simple compounds or the metabolism of pollutants in the phyllosphere and rhizosphere [11].

Transformation in the rhizosphere, also called rhizodegradation (or considered phytostimulation), is carried out by soil organisms such as bacteria, fungi or enzymes released from plants or microorganisms. Pollutants are degraded in the rhizosphere as well as inside plants by specific plant enzymes such as nitroreductases, dehalogenases, and laccases [25]. Compounds secreted from plants, such as sugars, amino acids or enzymes, can stimulate the growth of bacteria in the soil and vice versa – stimulate microbial and fungal degradation by releasing enzymes into the rhizosphere. That is why rhizodegradation is also called phytoremediation or bioremediation with the help of plants [11].

During photosynthesis, plants absorb VOCs through stomata and cuticle wax, subsequently converting them into amino acids through the Calvin cycle [26]. In the intercellular spaces of plants, absorbed pollutants are stored or react with the inner surface of leaves and the water film, then decompose or are released to the outside [26].

Other common gaseous air pollutants such as SO_2, CO_2, NO_x and O_3 also accumulate in plant cells and tissues, mainly through stomata, wax and cuticle. Photosynthesis is the basic plant mechanism in which plants absorb CO_2 and convert it into oxygen. Stomata located on the epidermis of leaves and stems of plants are the primary zone where the process of gas exchange takes place [27].

Considering the potential of plants to remove VOCs, there is some research on benzene removal. In [28], it was shown that the main agents for removing benzene, as one of the model VOCs, are microorganisms of the rhizosphere of potting mix. These studies were the first demonstration of microbial degradation of soil VOCs from the gaseous phase. The results demonstrate the ability of the microcosm created in the pots to contribute to indoor air purification and lay the foundation for the development of the plant and substrate system as an additional biofiltration system.

Sriprapat and Thiravetyan [29] provided experimental data for eight types of plants, including *Sansevieria trifasciata*, *Euphorbia milii*, *Epipremnum aureum*, *Syngonium podophyllum*, *Hedera helix*, *Chlorophytum comosum*, *Dracaena sanderiana* and *Clitoria ternatea* used to remove benzene from air and water. These houseplants are well known for their high tolerance to toxic pollutants. Within 96 hours, *C. comosum* was found to have the greatest potential among other plants to remove benzene from indoor air. The addition of bacteria showed a lower rate of benzene removal than in the absence of bacteria. Also, the efficiency of benzene removal by Chlorophytum comosum under conditions of light and darkness was considered in the work [23].

Some studies revealed that bacteria, which are concentrated on the surfaces of plant leaves, contribute to the biodegradation of VOCs [30]. Wetzel and Doucette [31] state that wax coating of cuticles on leaves can provide a simple, cost-effective way to sample indoor air for VOCs and help improve indoor air quality.

Correct selection of plant species plays an important role in removing VOCs from indoor air. Thus, in work [32], about 120 species of indoor plants were analysed by various researchers for the degree of VOC removal, which made it possible to draw the following conclusions:

- tropical indoor plants such as *Dracaena Janet Craig* and *Spathiphyllum* have low VOC removal activity [33];
- the best plants with high VOC removal: *Hemigraphis Alternata*, *Hosta* Purpleheart, *Hedera helix*, *Asparagus fern*, *Senecio Macroglossus 'Variegatus'*, and *Crassula portulacea.*

There is an interesting study that evaluated the potential of a *Spathiphyllum wallisii* to remove cigarette-derived VOCs and all particle size fractions [34], achieving a single-pass removal efficiency of 43.26 % for the total VOCs and 34.37 % for the total number of suspended particles. A botanical biofilter with a selected type of vegetation allowed the reduction of the concentration of many of harmful chemicals in tobacco smoke, including nicotine, limonene and toluene.

Usually, among volatile organic compounds, the main research of the scientific community is focused on formaldehyde. And phytoremediation is still the simplest and most environmentally safe technology for removing formaldehyde from indoor air [35]. Being toxic to humans and other living organisms due to, for example, DNA damage, formaldehyde is also an indispensable substance in plant metabolism [36]. According to the mass balance of water-air plant systems, the main mechanism of formaldehyde loss is the decomposition of formaldehyde in plant tissue caused by enzyme and redox reactions [37]. The redox mechanism shows that the rate of formaldehyde removal can be accelerated by increasing reactive oxygen species caused by ambient pressure [38].

Historically, the above-mentioned NASA studies on the purification of plants from formaldehyde in a closed environment used methods of formaldehyde absorption by plants in hanging pots, which also contributed to the study of formaldehyde absorption by leaf stomata [39] These methods have evolved into a modern automatic system for monitoring formaldehyde uptake by plants, which shows how fumigation increases hydroponic plants that are the most efficient for formaldehyde uptake [40]. Other factors affecting formaldehyde removal are the type of plants and the environment for their cultivation [28].

In [41], a number of experiments are given that demonstrate the absorption of formaldehyde by 376 different types of plants. Only five species ($\sim$1.3%) absorb more than 10 mg/m^2 of formaldehyde, while 90% of plants absorb less than 5 mg/m^2 of formaldehyde, with the majority of plant species belonging to the genus Tillandsia having a level of 97%, so can be recommended for indoor use.

The work [42] showed that *Epipremnum aureum* is one of the most effective plant species for formaldehyde absorption due to its high stomata and leaf area. In addition, in [43], an experiment was conducted on the removal of formaldehyde by such plant species as *Epipremnum aureum* and *Rohdea japonica* in a hermetic chamber. The results showed that the stems can also effectively remove formaldehyde. The results also showed that when plant leaves were exposed to formaldehyde, CO_2 concentration increased with decreasing formaldehyde concentration, and the change in CO_2 concentration could be used as an indicator of the degree of formaldehyde decontamination by plants.

In general, the ability of succulent plants and plants with lanceolate, hard, leathery leaves to absorb formaldehyde is relatively low [44].

Similarly, 50 terrestrial and 15 hydroponic plant species exhibiting high formaldehyde uptake capacity were also found to be related to light intensity, photosynthesis, and biomass [45]. Substrates for potted plants with high porosity, such as diatomite, peat, bark, sawdust, perlite, and bacterial residues, have a strong capacity to absorb formaldehyde [46]. In addition, it has been confirmed [47] that leaf age is very important for formaldehyde absorption efficiency, since young leaves have low stomatal conductance, while mature leaves have higher stomatal conductance for formaldehyde absorption.

Formaldehyde gas accumulates in the leaves of plants and transported to the roots from the rhizosphere zone. This transport mainly depends on the absorption time and formaldehyde content in the leaves. Microorganisms on the surface of the leaves also absorb formaldehyde, further enhancing this process.

Indoors with continuous release of formaldehyde, early-stage uptake is mainly by roots and soil, while plant leaves play a smaller role in the early stage and a greater role in the later stages [48].

Plants are known to be associated with symbiotic microbes such as fungi and bacteria that mitigate abiotic and biotic stresses in them and enhance their growth. Plant-microbe interactions also play an important role during phytoremediation by degrading, detoxifying, or sequestering pollutants [49].

Therefore, the composition of soil rhizosphere microorganisms also plays an important role in the absorption and metabolism of gaseous formaldehyde by plants [50]. In systems without rhizosphere microorganisms, formaldehyde is not removed, while in systems with a rhizosphere microbiome (10–45 mg/dm^3), all formaldehyde is removed [51].

Understanding the influence of rhizosphere microflora on formaldehyde metabolism is important to increase the efficiency of uptake and removal by houseplants [52].

The use of microorganisms can improve the remediation capacity of potted plants. The addition of cultivated microorganisms to the rhizosphere of such plant species as *Aloe vera* and *Tradescantia zebrine* improved the efficiency of formaldehyde removal [53]. In addition, a hydroponic system was developed that consisted of plants of the species *Ophiopogon japonicus*, phenol-degrading bacteria such as *Staphylococcus epidermis* and *Pseudomonas spp.* and air compressor. This system showed a high capacity for phenol decomposition of about 1000 g/dm^3 daily [53].

The authors [54] showed that the rate of formaldehyde removal is not only related to the size of plants in pots but also closely related to air dynamics. They used the parameter of equivalent clean air supply rate, which is commonly used to quantify air cleaning capacity, and showed that the investigated parameter is only 5.1 m^3/h per m^2 room for static air, and 233 m^3/h per m^2 room when the air was transported through potted plants.

On the other hand, work [55] shows that, according to the ASHRAE standard 62.1-2016, the minimum ventilation rate in the working zones of office premises is 0.3 dm^3/s for every m^2 of space (1.08 m^3/h for every square meter of space) [56]; similarly to the NEN-EN 15251-2007 standard, the minimum ventilation rate for new or reconstructed buildings is 0.35 dm^3/s for each m^2 of the room area (1.26 m^3/h for each square meter of area) [57].

In the standard [56], it was established that the rate of supply of clean air for formaldehyde removal by potted plants is 0.03 m^3/h, therefore, to meet the standards without an additional ventilation system, it is necessary to have 42 plants for every square meter of the room area.

In addition, the authors established [55] that the rate of supply of clean air for CO_2 depletion by plants in pots is 0.01 m^3/h (*Reace lily*) and 0.02 m^3/h (*Nephrolepis exaltata*). Therefore, it is necessary to have >100 plants for every square meter of room area to meet the standards without an additional ventilation system.

Despite the large number of works devoted to the study of the removal of VOCs from indoor air by plants [58, 59], there is still a need for additional research on the modification of plant physiology by, for example, rhizosphere modification to increase phytoremediation of indoor gaseous formaldehyde.

There is an inaccuracy related to volatile organic compounds. There is a subclass of it called volatile phytoorganic compounds, which contain healthy substances – phytoncides, odorants etc. But gas analysers often display total volatile organic compounds (TVOC) without division. When the authors perform experiments with plants, D91 gas analyser alerts the deadly content of TVOC, but the experimenters feel very good and stay healthy. Thus, we should be very careful interpreting the measuring results in greened rooms. When measuring the absorption of total volatile organic compounds by plants, the result will be always strictly underestimated or inverted. Thus, we can perform experiments only on individual compounds and only after testing the measuring sensors for the influence of volatile phytoorganic compounds. For example, we can bring the sensors to plants in a clean room and check the insignificance of rising the readings.

Phytoremediation was evaluated in [64] as a solution for trimethylamine (TMA) removal. Trimethylamine (TMA, N(CH3)3) is a volatile tertiary amine, which is a decomposition product of nitrogen-containing organic substances of animal and plant origin. It is a colourless gas that has a fishy odour at low concentrations and an ammonia-like odour at higher concentrations. Eight species of pot plants were used in the research: *Opuntia*, *Dracaena sanderiana*, *Dieffenbachia camilla*, *Tradescantia spathacea*, *Peperomia magnoliifolia*, *Chlorophytum comosum*, *Cereus hexagonus* (L.) Mill., and *Scindapsus aureus*, which were selected as candidates for TMA removal under light and dark conditions.

According to the research results, the authors divided the selected plants into two groups: plants with high TMA removal efficiency under light conditions and plants with high removal efficiency under light and dark conditions. The results showed that *S. aureus* had the highest TMA removal efficiency under light conditions after 72 hours (> 95 %). However, it had very low efficiency under dark conditions, suggesting that *S. aureus* should be housed in areas with 24-hour light sources. On the other hand, *cactus* species (*C. hexagonus* (L.) Mill. and *Opuntia*) remove TMA highly efficiently in both light and dark conditions after 72 hours (> 90 %) and therefore may be more suitable for real-world use. In addition, the ANOVA (analysis of variance) results confirm with 95 % confidence that plant type (chosen from 8 types) and lighting conditions (e.g., LED lighting, fluorescent lighting, or dark conditions) have a significant effect on TMA removal after 24 h.

2.3. Reducing the level of CO_2 *in a room*

Regarding the reduction of carbon dioxide (CO_2) levels and the expected level of air quality, the results showed a positive effect of indoor green spaces in reducing CO_2 levels [60]. In addition, the authors also found that the concentration of CO_2 changes depending on human activity inside the living space.

Thus, work [61] shows that in non-industrial premises, such as offices, schools and houses, the main source of CO_2 is human metabolism. In addition, it is justified that CO_2 is no longer considered a pollutant, but an indicator of the presence of pollutants associated with the presence of people indoors.

It has been proven [62] that indoor plants improve the indoor atmosphere, relieve anxiety and reduce CO_2 concentration. In addition, there are a number of studies that confirm the removal of other types of indoor air pollutants by potted plants. For example, in [63] the mechanisms of nitrogen oxide removal by dry deposition by potted plants were considered. The principle of absorption of pollutants by leaves and the factors affecting the removal of nitrogen oxides are substantiated, providing a theoretical basis for the selection of urban green vegetation.

2.4. Microorganisms

The work [1] shows the results of research based on the microbiota factor. The impact of plants on air quality was determined by monitoring the microbiological state of the air in several office premises in order to select promising plant species for creating health-improving interiors. Observational data demonstrate the bactericidal effect of the investigated phytoncide plants. It has been experimentally established that the microbial count in rooms with plants is significantly lower than in a reference room without plants. In the room with plants, the number of microorganisms was 1.5 ... 5 times less, depending on the period of observation. In addition, work [1] offers an assortment of plants, namely: *Ficus benjamina*, *Ficus benjamina Wiandi*, *Zamioculcas Zamiifolia*, *Dracaena marginata*, *Dracaena fragrans*, *Yucca elephantipes*, *Schefflera digitata*, *Aspidistra elatior*, *Crassula ovata*, *Spathiphyllum wallisii*.

2.5. Technology of active "green" structures for indoor air purification

Active "green" structures are one of the newest varieties of phytoremediation systems, which include ventilation, heating and cooling of the house using evaporative cooling – by the same principle as the cooling effect of outdoor green structures [3]. It operates on full recirculation, taking and returning the air to the room (figure 1).

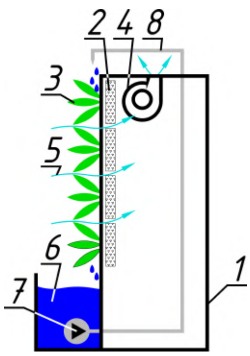

Figure 1. Active phytowall [65]: 1 – box; 2 – planting media; 3 – plants; 4 – fan; 5 – air movement; 6 – water tray; 7 – pump; 8 – pipe for watering.

The system of "green" walls, which cleans the air inside, also acts as a temperature and humidity control.

The authors [65] studied the system over 300 days. Satisfactory efficiency was found to remove formaldehyde and toluene (90 % and more than 33 %, respectively, during the first four days). In addition, this ACBB system successfully reduced the indoor air temperature by 0.5 °C in the real environment, while the temperature reduction was 1 °C in the laboratory. The increase in relative humidity for realistic and laboratory conditions was 17.7 and 9-13 %, respectively. In addition, a 20 % reduction in outside air supply was achieved with the ACBB system, saving the energy required by the building, given that the toluene and formaldehyde concentrations determined the standard ventilation rate for this case. Also, the analysis of the studied data confirmed the reduction of particulate matter (PM) concentrations to a level that the current indoor HVAC system could not achieve under normal conditions.

The same authors [65] also conducted many studies in laboratory conditions. The efficiency of the system in removing PM was evaluated exclusively in a static chamber, where a general observation recorded that the efficiency of PM removal increased with an increase in the airflow rate. Experiments were conducted with five different air flow rates to evaluate the efficiency of the ACBB system for filtering total suspended particles, PM 2.5 and PM 10. Based on the collected data and further analysis, this study estimates that for four workers in an office space, 1 m^2 of the system can sufficiently provide the necessary ventilation.

Therefore, since indoor air quality in buildings contributes to human health problems on a large scale, implementing sustainable solutions to maintain indoor air quality has become a particular challenge for the scientific community. Active botanical biofiltration systems are effective in removing pollutants along with the potential to increase humidity and cool the air. It is also well-studied that these systems do not promote the spread of fungi if they are maintained in a well-controlled state [66]. Moreover, the aesthetic value of the systems is an additional advantage for positive mental effects.

Since there is currently no software or computational methods capable of recognizing plants as indoor “air cleaners”, the impact of phytoremediation on the operation of HVAC systems and the energy sector is still poorly researched.

In the work [67], *Azolla filiculoides* was integrated into building walls for bioremediation of indoor air and a new protocol for assessing the effectiveness of a “green” wall using the “Indoor Air Quality” and “Ventilation Rate” techniques was proposed, which are recognized as practical engineering methods for determining the efficiency of air exchange using mechanical equipment. *Azolla filiculoides* has been observed to help absorb indoor CO_2, while under the Indoor Air Quality methodology, this results in a reduction in the building’s ventilation rate and, as a result, a reduction in the building’s overall energy consumption. In addition, the cooling effect of a green wall with *Azolla filiculoides* as a natural shading component was evaluated by applying its latent heat capacity to the thermal convection/conductivity of the facade, compared to aluminium louvres of the same size and spacing to computationally assess the thermal benefits of plants for improvement of cavity/inner space overheating.

So, based on the work [55], it is possible to define advantages regarding the effectiveness of the use of vegetation in rooms, which are based on scientific research over the past 30 years, of which the main ones are:

- Biophilic design and vegetation have a positive effect on people who spend a long time indoors, which is manifested in an increase in the general psychological satisfaction and mood of people.
- Evaporation of plants has been found to help lower ambient temperature, so this property of plants can be used to cool air and control humidity.
- It has been shown that green plants can be used to reduce the sound level – as a passive acoustic insulation system.
- The effect of vegetation on improving indoor air quality was analysed. However, there is still a lack of reliable and relevant data to understand the true pollutant removal mechanisms and factors in these systems (plant species, microorganism species, gas composition, light source, number of plants).
- It has been shown that in an active vegetation system (”green” systems in combination with mechanical fans) the rate of air purification can be significantly higher than in a passive vegetation system (potted plants).

Nevertheless, no attention is paid to the time, when plants don’t release oxygen. The daily biorythms of plants weren’t analysed, which can principally change the conclusions. Thus, we need to focus on this challenge to avoid troubles in the corresponding daytime.

3. Materials and methods

The literature review shows the most naturally promising approach for air quality control – plants [1, 2, 11, 68, 69]. They continuously humidify the air, remove volatile chemicals, dust, and other impurities, and release valuable volatile phytoorganic substances such as odorants and phytoncides. The last ones are the immunity substances that kill viruses and bacteria.

During active oxygen release time, plants emit oxygen while absorbing CO_2 [70, 71]. At other times, plants breathe only and pollute the surrounding air by CO_2. Except for [72] Crassulacean acid metabolism (CAM), which releases oxygen at night, most plants produce oxygen during the day.

To check the overall effect, we can analyse the outcomes of the *Aglaonema roebelinii* testing conducted by Intell House [73]. To control illumination, the researchers use two packets – light-tight and transparent. The measurements were performed using NetAtmo Weather Station. In the first packet, the CO_2 content increases from 796 to 2311 ppm within 40 minutes. The concentration in the transparent packet under the sun decreases from 1060 to 315 ppm. The concentration starts to rise at 16:06, reaches 1572 ppm at 6:54 and decreases to 263 ppm in the morning. The researchers concluded of no overall oxygenation during the day. The experimental method is very simple and didn't take into account many factors such as the dependency of photosynthesis on CO_2 content. But we can conclude that in the less favourable case, the CO_2 and oxygen emissions are balanced per day without overall CO_2 gain to the environment. It's good for us because phytofiltration will never cause greenhouse gas emissions. The second important conclusion is that we should develop a new phytofilter that operates accordingly to the plant's biorhythms to avoid temporary pollution of the inlet/indoor air. To continuously reduce indoor and outdoor air pollution and oxygenate the inlet/indoor air, active oxygen release should be carried out in the inlet air and breathing only in the exhaust.

4. Results and discussion

We suggest a design for an inlet-exhaust ventilation phytofilter module (figure 2). The phytofilter contains a valve system 4, which controls the airflow through spaces with plants 3 and the corresponding illumination 5. Ducts 1 should be connected to inlet and outlet ventilation ducts or an air handling unit. Controller 6 switches illumination 5 by rotation to keep artificial biorhythms of the plants inside. Some spaces 3 can be equipped with glazing to utilize natural light. The valves are opened-closed together with the illumination to pass inlet air through space(s) 3 with oxygen release and outlet one – through other spaces 3. For 24/7 operation with most plants, the phytofilter should contain at least three cameras. But for working time up to 16 h/day two cameras will be enough.

The main problem is the energy consumption of phytolamps. It's impossible to split oxyden and carbon from CO_2 without energy consumption because in the opposite case, we will obtain perpetum mobile by burning the carbon. Thus we should find opportunities to use free accessible energy for illumination or utilise the heat from the lamp. There are some ways:

- utilizing natural illumination only through transparent walls demands the combination of CAM and other plants, but this raises biomass requirements due to CAM's reduced efficiency as a result of its overnight energy discharge and daily energy charge, so the exergy destruction will occur twice;
- the use of natural illumination for spaces with daily oxygen release;
- the phytofilter should be installed after an air-handling unit with the heater, cooler, and re-heater (figure 2), thus the heat from illumination will reduce the requirement for energy

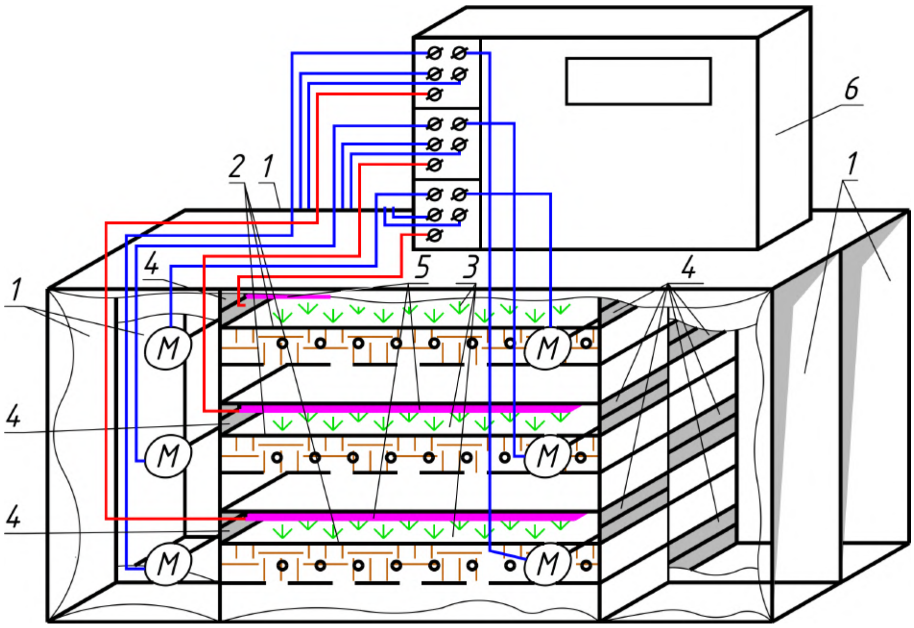

Figure 2. Phytofilter: 1 – duct; 2 – planting tray with irrigation and drainage; 3 – space with plants to pass inlet or outlet air depending on the current gas exchange; 4 – motored valve; 5 – illumination (we recommend growing LED phytolamps); 6 – controller of illumination and valves

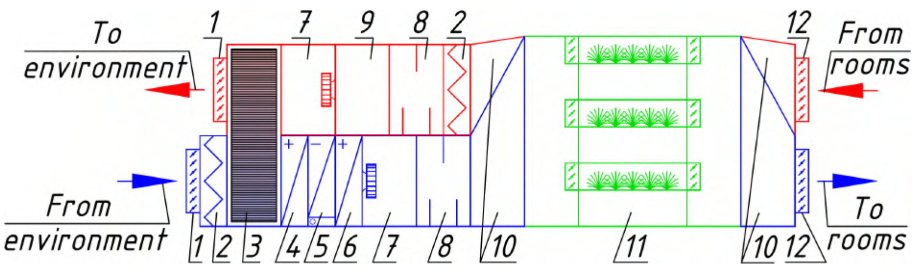

Figure 3. Installation of phytofilter: 1-9 – inlet-exhaust air handling unit; 1 – thermal-insulated valve; 2 – filter; 3 – heat recovery unit (in this scheme – rotor regenerator); 4 – heater; 5 – cooler with condensate diversion; 6 –re-heater; 7 – fan; 8 – sound attenuator; 9 – empty section; 10 – double 3D adapter; 11 – phytofilter; 12 – valve

for air heating in the heating period and re-heating in the cooling period, which almost eliminates additional energy consumption.

We require tiny plants with highly efficient photosynthesis and cleaning for a compact design. The suggested selection is *Chlorophytum comosum*, *Aglaonema Modestum*, *A. pictum*, *A. plumosus*, *A. silver Bay*, *Aloe aristata*, *A.parvula*, *Asparagus plumosus*, *Kalanchoe blossfeldiana*, *Pelargonium tomentosum*, *Philodendron scandens*, *Sansevieria trifasciata* “Hahnii”, *Spathiphillum wallisii*.

If some of the suggested plants grow larger than necessary, trimming can readily fix their crown size. It’s possible to use the secondary materials for substratum, for example, broken bricks or wood after shelling from the russian federation. The main condition is to avoid secondary pollution. For example, particle boards are not suitable.

5. Conclusions

Phytoremediation is a perspective technology for increasing outdoor and indoor air quality. It allows for decreasing VOCs and microbes. But known indoor phytoremediation systems don't take into account plant biorhythms, which causes secondary CO_2 air pollution. We propose a new ventilation phytofilter, which can organise airflows to achieve two goals simultaneously: cleaning and oxygenating inlet air 24/7 and cleaning exhaust air to make a building more environment-friendly, which is very important for densely-built districts.

The continuation of the research is creating and testing experimental models of the phytofilter. Now we are researching gas exchange in plants using a gas-exchange camera in the Laboratory of Heat-Mass Exchange in Green Structures. The results will allow calculation the required biomass. The most throttling factor is the war of the russian federation against Ukraine, which significantly reduce sponsorship possibilities.

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References

[1] Tkachenko T and Mileikovskyi V 2019 Solution of sick building syndrome problem using indoor plants *Environmental Innovations: Advances in Engineering, Technology and Management, EIAETM, 23rd-27th September, 2019* (*Procedia ESEM* vol 6) ed Vučinić D, Yudakov A A, Pinchuk V A and Kuzmin A V (Cluj-Napoca: SNSIM) pp 405–411 URL http://procedia-esem.eu/pdf/issues/2019/no3/48_Tkachenko_19.pdf

[2] Tkachenko T, Mileikovskyi V, Dziubenko V and Tkachenko O 2020 *IOP Conference Series: Materials Science and Engineering* **907**(1) 012064 URL https://doi.org/10.1088/1757-899X/907/1/012064

[3] Tkachenko T and Mileikovskyi V 2020 *Songklanakarin Journal of Science and Technology (SJST)* **42** 50–56 URL https://doi.org/10.14456/sjst-psu.2020.8

[4] Tkachenko T and Mileikovskyi V 2019 Geometric Basis of the Use of "Green Constructions" for Sun Protection of Glazing *ICGG 2018 - Proceedings of the 18th International Conference on Geometry and Graphics* ed Cocchiarella L (Cham: Springer International Publishing) pp 1096–1107 ISBN 978-3-319-95588-9 URL https://doi.org/10.1007/978-3-319-95588-9_94

[5] Tkachenko T and Mileikovskyi V 2021 Assessment of Light Transmission for Comfort and Energy Efficient Insolation by "Green Structures" *ICGG 2020 - Proceedings of the 19th International Conference on Geometry and Graphics* ed Cheng L Y (Cham: Springer International Publishing) pp 139–151 ISBN 978-3-030-63403-2 URL https://doi.org/10.1007/978-3-030-63403-2_13

[6] Tkachenko T 2018 *International Journal of Engineering & Technology* **7**(3.2) 453–457 URL https://www.researchgate.net/publication/326148772

[7] Mileikovskyi V and Tkachenko T 2021 Precise Explicit Approximations of the Colebrook-White Equation for Engineering Systems *Proceedings of EcoComfort 2020* ed Blikharskyy Z (Cham: Springer International Publishing) pp 303–310 ISBN 978-3-030-57340-9 URL https://doi.org/10.1007/978-3-030-57340-9_37

[8] Gawronski S W, Gawronska H, Lomnicki S, Sæbo A and Vangronsveld J 2017 Chapter Eight - Plants in Air Phytoremediation *Phytoremediation* (*Advances in Botanical Research* vol 83) ed Cuypers A and

Vangronsveld J (Academic Press) pp 319–346 URL https://www.sciencedirect.com/science/article/pii/S0065229616301276
[9] Rostami S and Azhdarpoor A 2019 *Chemosphere* **220** 818–827 ISSN 0045-6535 URL https://doi.org/10.1016/j.chemosphere.2018.12.203
[10] Bandehali S, Miri T, Onyeaka H and Kumar P 2021 *Atmosphere* **12**(4) 473 ISSN 2073-4433 URL https://doi.org/10.3390/atmos12040473
[11] Cakyova K, Vertal M, Vystrcil J, Nespesny O, Beckovsky D, Rubina A, Pencik J and Vranayova Z 2021 *Sustainability* **13**(21) 11649 ISSN 2071-1050 URL https://doi.org/10.3390/su132111649
[12] Wolverton B C, Douglas W L and Bounds K 1989 A Study of Interior Landscape Plants for Indoor Air Pollution Abatement Technical Memorandum NASA-TM-108061 NASA URL https://ntrs.nasa.gov/citations/19930072988
[13] Pottorff L 2016 Plants "Clean" Air Inside Our Homes URL http://www.aergrow.com/blog-1/2016/4/14/plants-clean-air-inside-our-homes
[14] Wolverton B C, Mcdonald R C and Watkins E A 1984 *Economic Botany* **38**(2) 224–228 ISSN 1874-9364 URL https://doi.org/10.1007/BF02858837
[15] Wolverton B C 1997 *How to Grow Fresh Air: 50 House Plants that Purify Your Home or Office* (London, UK: Penguin Books)
[16] Wolverton B C and Wolverton J D 1993 *Journal of the Mississippi Academy of Sciences* **38**(2) 11–15 ISSN 0076-9436 URL http://web.archive.org/web/20060312104216if_/http://www.wolvertonenvironmental.com/MsAcad-93.pdf
[17] Tabak H H, Quave S A, Mashni C I and Barth E F 1981 *Journal (Water Pollution Control Federation)* **53**(10) 1503–1518 ISSN 00431303 URL http://www.jstor.org/stable/25041532
[18] Gawrońska H and Bakera B 2015 *Air Quality, Atmosphere & Health* **8**(3) 265–272 ISSN 1873-9326 URL https://doi.org/10.1007/s11869-014-0285-4
[19] Su Y and Liang Y 2015 *Journal of Hazardous Materials* **291** 120–128 ISSN 0304-3894 URL https://doi.org/10.1016/j.jhazmat.2015.03.001
[20] Pettit T, Irga P J and Torpy F R 2019 *Air Quality, Atmosphere & Health* **12**(1) 33–44 ISSN 1873-9326 URL https://doi.org/10.1007/s11869-018-0628-7
[21] Suárez-Cáceres G P, Fernández-Cañero R, Fernández-Espinosa A J, Rossini-Oliva S, Franco-Salas A and Pérez-Urrestarazu L 2021 *Atmospheric Pollution Research* **12**(3) 224–229 ISSN 1309-1042 URL https://doi.org/10.1016/j.apr.2020.11.009
[22] Llewellyn D and Dixon M 2011 4.26 - Can Plants Really Improve Indoor Air Quality? *Comprehensive Biotechnology (Second Edition)* ed Moo-Young M (Burlington: Academic Press) pp 331–338 second edition ed ISBN 978-0-08-088504-9 URL https://doi.org/10.1016/B978-0-08-088504-9.00325-1
[23] Treesubsuntorn C, Lakaew K, Autarmat S and Thiravetyan P 2020 *Acta Astronautica* **175** 396–404 ISSN 0094-5765 URL https://doi.org/10.1016/j.actaastro.2020.05.061
[24] Dela Cruz M, Christensen J H, Thomsen J D and Müller R 2014 *Environmental Science and Pollution Research* **21**(24) 13909–13928 ISSN 1614-7499 URL https://doi.org/10.1007/s11356-014-3240-x
[25] Lee B X Y, Hadibarata T and Yuniarto A 2020 *Water, Air, & Soil Pollution* **231**(8) 437 ISSN 1573-2932 URL https://doi.org/10.1007/s11270-020-04813-6
[26] Wei Z, Van Le Q, Peng W, Yang Y, Yang H, Gu H, Lam S S and Sonne C 2021 *Journal of Hazardous Materials* **403** 123658 ISSN 0304-3894 URL https://doi.org/10.1016/j.jhazmat.2020.123658
[27] Omasa K, Tobe K and Kondo T 2002 Absorption of Organic and Inorganic Air Pollutants by Plants *Air Pollution and Plant Biotechnology: Prospects for Phytomonitoring and Phytoremediation* ed Omasa K, Saji H, Youssefian S and Kondo N (Tokyo: Springer Japan) pp 155–178 ISBN 978-4-431-68388-9 URL https://doi.org/10.1007/978-4-431-68388-9_8
[28] Orwell R L, Wood R L, Tarran J, Torpy F and Burchett M D 2004 *Water, Air, and Soil Pollution* **157**(1) 193–207 ISSN 1573-2932 URL https://doi.org/10.1023/B:WATE.0000038896.55713.5b
[29] Sriprapat W and Thiravetyan P 2016 *International Biodeterioration & Biodegradation* **113** 262–268 ISSN 0964-8305 challenges in Environmental Science and Engieering – 2015 URL https://doi.org/10.1016/j.ibiod.2016.03.001
[30] Sandhu A, Halverson L J and Beattie G A 2007 *Environmental Microbiology* **9**(2) 383–392 URL https://doi.org/10.1111/j.1462-2920.2006.01149.x
[31] Wetzel T A and Doucette W J 2015 *Chemosphere* **122** 32–37 ISSN 0045-6535 URL https://doi.org/10.1016/j.chemosphere.2014.10.065
[32] Soreanu G, Dixon M and Darlington A 2013 *Chemical Engineering Journal* **229** 585–594 ISSN 1385-8947 URL https://doi.org/10.1016/j.cej.2013.06.074
[33] Yang D S, Pennisi S V, Son K C and Kays S J 2009 *HortScience horts* **44**(5) 1377 – 1381 URL https://doi.org/10.21273/HORTSCI.44.5.1377

[34] Morgan A L, Torpy F R, Irga P J, Fleck R, Gill R L and Pettit T 2022 *Chemosphere* **295** 133942 ISSN 0045-6535 URL https://doi.org/10.1016/j.chemosphere.2022.133942
[35] Han Y, Lee J, Haiping G, Kim K H, Wanxi P, Bhardwaj N, Oh J M and Brown R J C 2022 *Journal of Environmental Management* **301** 113860 ISSN 0301-4797 URL https://doi.org/10.1016/j.jenvman.2021.113860
[36] Solomon M J, Larsen P L and Varshavsky A 1988 *Cell* **53**(6) 937–947 ISSN 0092-8674 URL https://doi.org/10.1016/S0092-8674(88)90469-2
[37] Wang R, Zeng Z, Guo H, Tan H, Liu A, Zhao Y and Chen L 2018 *Planta* **247**(2) 339–354 ISSN 1432-2048 URL https://doi.org/10.1007/s00425-017-2790-9
[38] Su Y, Liang H, Zhao S and Liu K 2019 *Human and Ecological Risk Assessment: An International Journal* **25**(4) 1059–1071 URL https://doi.org/10.1080/10807039.2018.1474432
[39] Irga P J, Pettit T J and Torpy F R 2018 *Reviews in Environmental Science and Bio/Technology* **17**(2) 395–415 ISSN 1572-9826 URL https://doi.org/10.1007/s11157-018-9465-2
[40] Zhao S, Su Y and Liang H 2019 *Journal of Environmental Health Science and Engineering* **17**(1) 141–150 ISSN 2052-336X URL https://doi.org/10.1007/s40201-018-00335-w
[41] Peng W X, Yue X, Chen H, Ma N L, Quan Z, Yu Q, Wei Z, Guan R, Lam S S, Rinklebe J, Zhang D, Zhang B, Bolan N, Kirkham M and Sonne C 2022 *Journal of Hazardous Materials* **436** 129304 ISSN 0304-3894 URL https://doi.org/10.1016/j.jhazmat.2022.129304
[42] Feng L, He S, Wei L, Zhang J and Wu H 2021 *Environmental Research* **200** 111415 ISSN 0013-9351 URL https://doi.org/10.1016/j.envres.2021.111415
[43] Zuo L, Wu D, Yu L and Yuan Y 2022 *Environmental Science and Pollution Research* **29**(8) 11445–11454 ISSN 1614-7499 URL https://doi.org/10.1007/s11356-021-16571-x
[44] Liu Y, Yuan Y, yu Lei X, Yang H, Ibrahim S A and Huang W 2013 *Food Chemistry* **138**(4) 2174–2179 ISSN 0308-8146 URL https://doi.org/10.1016/j.foodchem.2012.12.038
[45] Wang L, Sheng Q, Zhang Y, Xu J, Zhang H and Zhu Z 2020 *Environmental Pollution* **265** 115003 ISSN 0269-7491 URL https://doi.org/10.1016/j.envpol.2020.115003
[46] Teiri H, Pourzamani H and Hajizadeh Y 2018 *Chemosphere* **197** 375–381 ISSN 0045-6535 URL https://doi.org/10.1016/j.chemosphere.2018.01.078
[47] Rottenberger S, Kuhn U, Wolf A, Schebeske G, Oliva S T, Tavares T M and Kesselmeier J 2005 *Atmospheric Environment* **39**(12) 2275–2279 ISSN 1352-2310 URL https://doi.org/10.1016/j.atmosenv.2004.12.027
[48] Lee J H 2013 *Biotechnology and Bioprocess Engineering* **18**(3) 431–439 ISSN 1976-3816 URL https://doi.org/10.1007/s12257-013-0193-8
[49] James A 2022 Phytoremediation of Urban Air Pollutants *Urban Ecology and Global Climate Change* (John Wiley & Sons, Ltd) chap 8, pp 140–161 ISBN 9781119807216 URL https://doi.org/10.1002/9781119807216.ch8
[50] Oyabu T, Sawada A, Onodera T, Takenaka K and Wolverton B 2003 *Sensors and Actuators B: Chemical* **89**(1) 131–136 ISSN 0925-4005 URL https://doi.org/10.1016/S0925-4005(02)00454-9
[51] Seco R, Peñuelas J and Filella I 2008 *Atmospheric Environment* **42**(34) 7907–7914 ISSN 1352-2310 URL https://doi.org/10.1016/j.atmosenv.2008.07.006
[52] Zhong J, Li J, Zhan T, Liu Q, Yang H, Guo D and Yan L 2020 *Research of Environmental Sciences* **33** 341–348 ISSN 1001-6929 URL https://doi.org/10.13198/j.issn.1001-6929.2019.04.18
[53] Yang Y, Su Y and Zhao S 2020 *Environmental Chemistry Letters* **18**(1) 197–206 ISSN 1610-3661 URL https://doi.org/10.1007/s10311-019-00922-9
[54] Wang Z, Pei J and Zhang J S 2014 *Journal of Hazardous Materials* **280** 235–243 ISSN 0304-3894 URL https://doi.org/10.1016/j.jhazmat.2014.07.059
[55] Moya T A, van den Dobbelsteen A, Ottelé M and Bluyssen P M 2019 *Indoor and Built Environment* **28**(3) 298–309 URL https://doi.org/10.1177/1420326X18783042
[56] 2022 ANSI/ASHRAE Standard 62.1-2022, Ventilation and Acceptable Indoor Air Quality URL https://www.ashrae.org/technical-resources/bookstore/standards-62-1-62-2
[57] 2006 Indoor environmental input parameters for design and assessment of energy performance of buildings-addressing indoor air quality, thermal environment, lighting and acoustics European Standard prENrev 15251:2006 (E) European Committee for Standardization Brussels, Belgium URL https://bit.ly/3LQWIvx
[58] Khalifa A A, Khan E and Akhtar M S 2023 *International Journal of Phytoremediation* **25**(4) 493–504 URL https://doi.org/10.1080/15226514.2022.2090499
[59] Di Talia V and Antonioni G 2022 *Chemical Engineering Transactions* **91** 571–576 URL https://doi.org/10.3303/CET2291096
[60] Cetin M and Sevik H 2016 *Polish Journal of Environmental Studies* **25**(3) 973–979 ISSN 1230-1485 URL

https://doi.org/10.15244/pjoes/61744
[61] Zhang X, Wargocki P, Lian Z and Thyregod C 2017 *Indoor Air* **27**(1) 47–64 URL https://onlinelibrary.wiley.com/doi/abs/10.1111/ina.12284
[62] Liu F, Yan L, Meng X and Zhang C 2022 *Journal of Building Engineering* **53** 104542 ISSN 2352-7102 URL https://doi.org/10.1016/j.jobe.2022.104542
[63] Li M, Gu H, Lam S S, Sonne C and Peng W 2022 *Environmental Pollution* **308** 119706 ISSN 0269-7491 URL https://doi.org/10.1016/j.envpol.2022.119706
[64] Wannomai T, Kemacheevakul P and Thiravetyan P 2019 *Aerosol and Air Quality Research* **19**(5) 1105–1113 URL https://doi.org/10.4209/aaqr.2018.09.0334
[65] Mannan M and Al-Ghamdi S G 2021 *Frontiers in Built Environment* **7** ISSN 2297-3362 URL https://doi.org/10.3389/fbuil.2021.672102
[66] Fleck R, Gill R L, Pettit T, Irga P J, Williams N L R, Seymour J R and Torpy F R 2020 *Building and Environment* **179** 106987 ISSN 0360-1323 URL https://doi.org/10.1016/j.buildenv.2020.106987
[67] Parhizkar H, Khoraskani R A and Tahbaz M 2020 *Journal of Cleaner Production* **249** 119313 ISSN 0959-6526 URL https://doi.org/10.1016/j.jclepro.2019.119313
[68] Cakyova K, Vertal M, Vystrcil J, Nespesny O, Beckovsky D, Rubina A, Pencik J and Vranayova Z 2021 *Sustainability* **13**(21) 11649 ISSN 2071-1050 URL https://doi.org/10.3390/su132111649
[69] Armijos-Moya T, de Visser P, Ottelé M, van den Dobbelsteen A and Bluyssen P M 2021 *Applied Sciences* **12**(1) 284 ISSN 2076-3417 URL https://doi.org/10.3390/app12010284
[70] Nayak N, Mehrotra R and Mehrotra S 2022 *Carbon Capture Science & Technology* **4** 100065 ISSN 2772-6568 URL https://doi.org/10.1016/j.ccst.2022.100065
[71] Khodakarami L, Pourmanafi S, Soffianian A R and Lotfi A 2022 *Earth and Space Science* **9**(7) e2022EA002261 URL https://doi.org/10.1029/2022EA002261
[72] Sand-Jensen K, Borum J, Møller C L and Baastrup-Spohr L 2022 *Plants* **11**(13) 1683 ISSN 2223-7747 URL https://doi.org/10.3390/plants11131683
[73] Intell House 2014 Smogut li komnatnye rasteniia izbavit nas ot uglekislogo gaza v pomeshchenii? (1 chast) [Can indoor plants rid us of indoor carbon dioxide? (part 1)] URL http://ihe.ru/articles/o_vozduhe/uglekisliy_gaz_i_fotosintez/

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Information system of multi-stage analysis of the building of object models on a construction site

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Information system of multi-stage analysis of the building of object models on a construction site

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Abstract. This study focuses on the development of a multi-stage analysis of building object models (BOM) on a construction site for modeling an "evolutionary" digital twin, by integrating building information modeling (BIM) technology and an artificial intelligence system. The concepts of photo modeling of the construction site using a group of moving cameras were outlined, as well as the possibility of integrating IoT technologies. The dynamic transition of real building structures into intermediate BIM representations of digital twins was investigated, with the prospect of enabling augmented reality technology. An artificial intelligence system combining Convolutional Neural Network (CNN) and Feed Forward Neural Network (FFNN) architectures has been developed as a comprehensive mechanism for the detection, categorization, and evaluation of BIM projects at all stages of their life cycle. The paper addresses the scaling prospects for the development of point cloud and mesh models, as well as the use of big data technology while optimizing the representation of the "evolutionary" BIM project of the digital twin of the construction site. The effectiveness of site conformance detection during the step-by-step construction of a BIM model, which shows consistency and provides a quantitative assessment of the processes occurring on the site, has been determined. The results of this research can be used to improve BIM modeling methods and concepts, in particular towards a multi-stage "evolutionary" representation of the digital twin of the construction site.

1. Introduction

Nowadays, BIM technologies have attained an extraordinary level of integration with many new technologies, such as artificial intelligence, the Internet of Things (IoT), Big Data, and Augmented Reality (AR), which has significantly increased the quality and speed of the entire set of operations and processes related to construction project modeling, implementation, and support. The generation of digital twins of the BOM and the construction site, in general, was an essential branch of the direction.

The purpose of this research is to provide scientific support for the concepts of multi-stage modelling of building site objects utilizing artificial intelligence based on BIM technology. The author's team created a concept that defines the BOM creation process in the BIM system as being separated into an arbitrary number of pieces on a suitable timetable. Such changes enable the formation of a model with distinct evolutionary development and growth dynamics. The implementation of a Structure from Motion (SfM) system, which will allow the creation of digital models from photographs from the construction site and displays a three-dimensional depiction of the state of the BOM in real-time, is critical to the collection of training and learning data. This technology will enable neural networks to categorize not only one representation of a BOM picture, but three reciprocal representations at the same time, namely point clouds, mesh models, and the BOM itself. These will enable the YOLOv5 and FFNN artificial intelligence models to identify faults more precisely during the execution of the BOM on the construction site.

Deng et al conducted a rigorous theoretical investigation of the development of BIM technologies across time. According to the paper [1], BIM technologies have evolved in five stages, as shown below:

Level 1. Static 3D BIM visualization tool;

Level 2. BIM model analyses and simulations;

Level 3. BIM and IoT method integration;

Level 4. BIM and artificial intelligence methods integration;

Level 5. Make a digital twin.

It is vital to highlight that in order to accomplish the fifth level, all preceding levels must be implemented in a single BIM project.

In scientific publications [2–4] the authors consider SfM systems when resolving problems by building three-dimensional models from a point cloud using photometry or videometry. Scientists list a wide variety of uses for SfM systems, such as simulating worker evacuation from a construction site to visualize the site's actual condition, reducing variance between planned and actual conditions, and creating an "as-built" model of an object based on an image of it for reconstruction. Also defined is the ability to interact with images taken by SfM in real-time and by BIM standards. Geometric information is extracted using three-dimensional grid models utilizing tools such as Meshroom (AliceVision 2020), Agisoft Photoscan, or COLMAP.

In the studies [5–7] scientists take intelligent technologies, including SfM, into consideration and find that when scaling projects, they frequently lead to Big Data, which in turn necessitates the use of advanced management, diagnostics, and forecasting from the executors and visualization of this data, in particular, using modern capabilities of The idea of big data analysis is also given a lot of attention since it makes it possible to address several issues linked to the productivity and digitization of different spheres of human activity. As a result, machine learning, intelligent data analysis techniques, and a variety of statistics have all been included in big data analytics.

In papers [8, 9], researchers examine BIM building employing IoT analysis. In addition, the authors determine the considerable importance of high-tech cloud solutions in connecting to the IoT. Given the expansion of BIM technology, it is expedient and important to use IoT, which is defined as a combination of physical and virtual components such as sensors, mechanisms, cloud services, communications, and protocols, to create digital twins of BOM and construction sites. This serves as the foundation for IoT systems.

Sezen et al [10] conduct an experimental study where they investigate precision, recall and mean average precision (mAP) are used as evaluation metrics among YOLOv3, YOLOv4, YOLOv5, and Faster R-CNN algorithms. Thus, based on the results of model training and direct tests, it was concluded that model YOLOv5 is the fastest and most productive when compared to YOLOv4 and others.

Dolhopolov et al [11] provided a practical example of how to employ multi-label classification with FFNN to address issues with a sizable number of input and output classes and the potential to scale into Big Data problems. The design of FFNN is impacted by the duties assigned to the performers, according to the findings of scientific research. To illustrate the parameter space, for instance, training on several parameters is necessary when doing a regression on multiple parameters.

The goal of this research is to provide an analytical foundation for an information system that will allow the concept of multi-stage modeling of building site objects using artificial intelligence based on BIM technology to be confirmed. Achieving this goal may result in the development of a quality standard for working with homogeneous BOMs, which will be decided by the intricate interaction of IoT, Big Data, BIM, YOLOv5, SfM, and FFNN.

2. Materials and method

Considering a complete examination of the scientific works of scientists of various profiles and proving the concept of multi-stage modeling of construction site objects using artificial intelligence based on BIM technology. Figure 1 shows the developed model of an information system that allows you to study a construction object or construction site in real-time and highlight aspects that allow you to model the representation of a construction object in a three-dimensional projection using SfM and IoT cameras. As a result, point clouds, mesh models, and BOMs with varied levels of detail are modeled. In the architecture of YOLOv5, each model of a building object is described as a class, allowing artificial intelligence to identify many photographs based on the stages of execution of the object on the construction site. The categorization data is then sent to the FFNN, which is compared to the standardized data that the project customer expects. As a result, the system's last procedure is to give the user information about the compliance of a certain building object with the standards, which can be determined manually or based on the pre-formed Dataset BOM. The unique feature of this information system's operation is the ability to determine whether the derived models of the architectural item reflect its general trends.

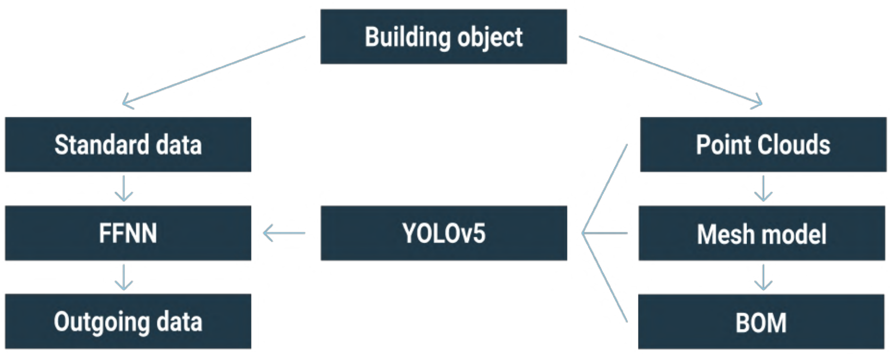

Figure 1. Multi-stage modeling of building site items in an information system model.

The process of obtaining information, known as photo modeling or videometry, is carried out via IoT devices, which can be used in two ways. Figure 2 shows static photo modeling, which is distinguished by the fact that cameras are installed just once and are utilized throughout the whole observation process, and dynamic photo modeling, which may not require the installation of as many cameras and is in motion at specific time intervals.

The advantages of the first method are complete autonomy and reliability of the data collection procedure. However, in the case of a big-scale construction project, a large amount of equipment may be necessary, which is why, in some circumstances, dynamic photo modeling is preferable, especially if building operations are slow.

Thus, within the framework of the study, we have the opportunity to extract information from panoramic photos or photo sequences and model on their basis Point Clouds, Mesh models, and

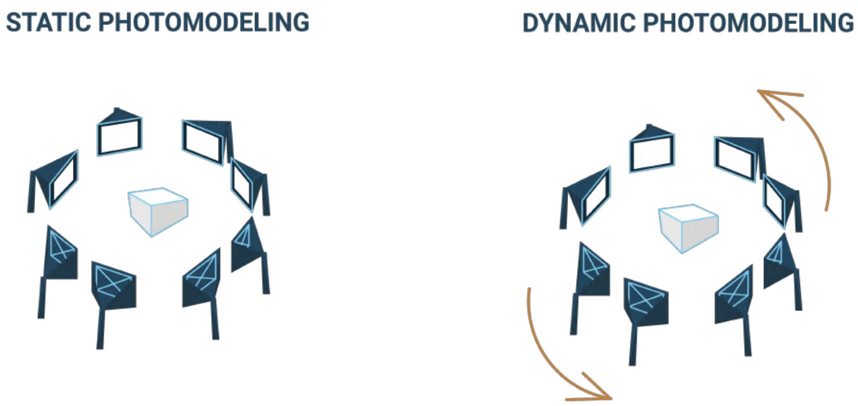

Figure 2. Possibilities for implementing photo modeling of the modeled building object.

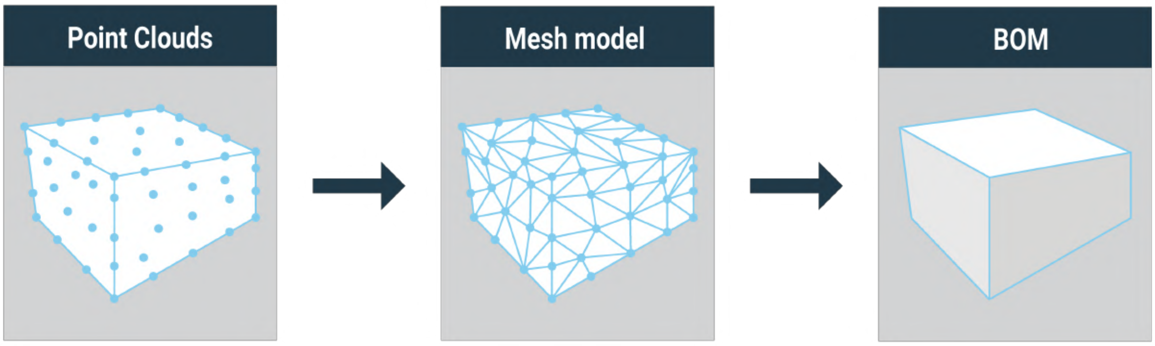

Figure 3. The BOM building process employs photo modeling and SfM.

BOMs of varying degrees of detail based on the project requirements using photo modeling and SfM, which is based on the Agisoft Photoscan software. Geometric forms are replicated with varying degrees of detail during photo modeling (approximately one point for every 5 cm of real size). The higher the image quality, the more detail is captured and the more natural it appears. In practice, however, different sets of input photos are frequently required. Figure 3 shows the BOM construction process utilizing photo modeling and SfM.

Within the scope of the project, 600 visualizations of BOM construction fragments were performed at various time intervals and construction objects, forming the study's learning and training Dataset. Figure 4 shows one of the BOM construction fragments on a real-world example of a building object with serial №5.

A dataset of 600 complete images of the building object was created as part of the study's framework (i.e., 2400 images representing the building object, Point Clouds, BOM, and Mesh Model). The artificial intelligence system recognizes diverse construction sites and their resulting models before determining their resemblance and compliance with the defined standard. Following the development of the models, they were manually tagged for additional training. Given the YOLOv5 model's excellent performance as the fastest and most successful model in the YOLO family, it was chosen for the categorization of building items and their derived models. Experiment results showed that 100 iterations of training took no more than 8 minutes of real-time.

The evaluation metrics chosen were Average Precision – the average accuracy for a given

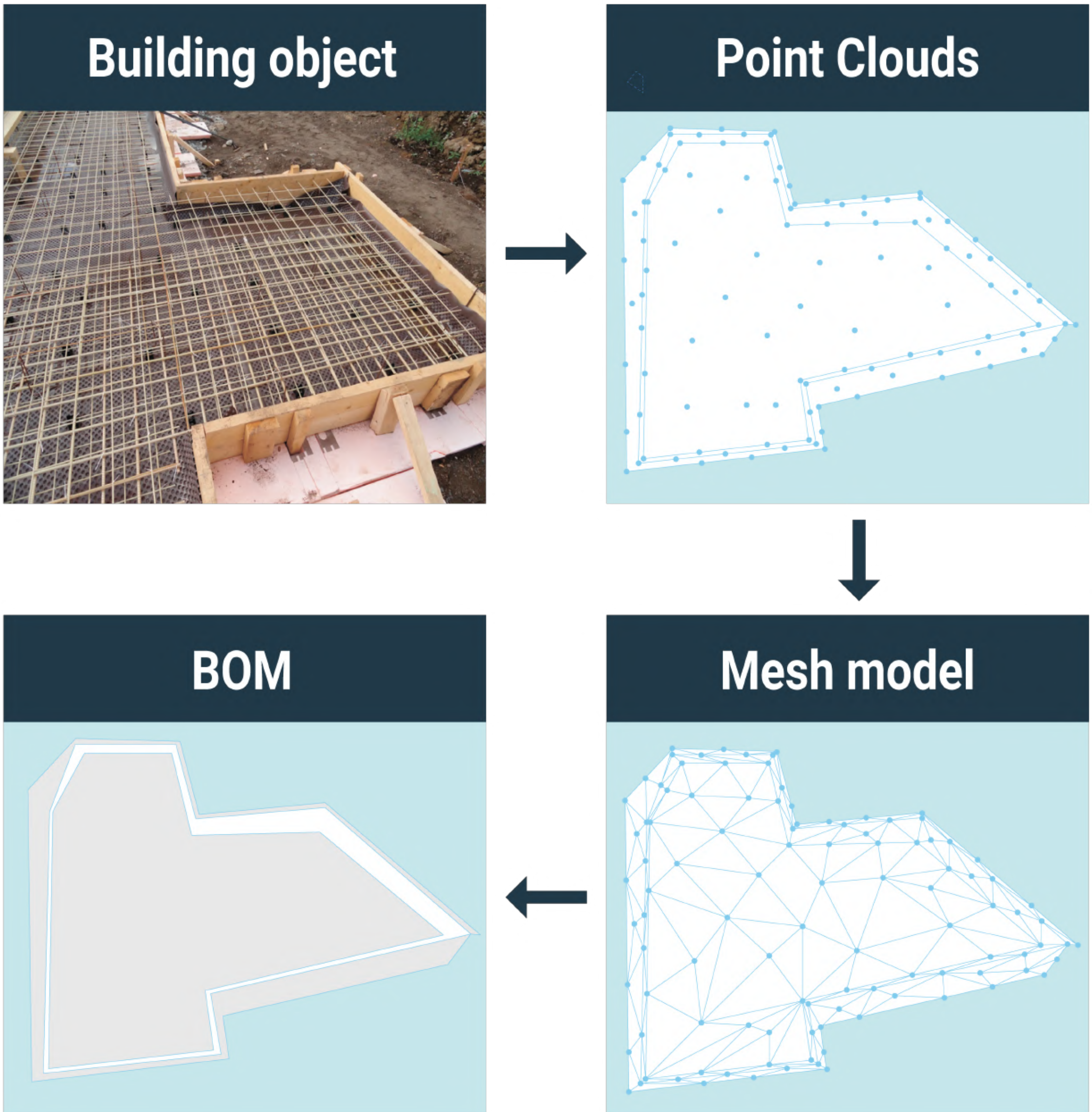

Figure 4. BOM construction using photo modeling and SfM for sample №5.

class, and Mean Average Precision (mAP) – the average accuracy for all classes.

The value of the average precision of the Point Clouds model is determined by equation:

$$AP_{PC} = \frac{\sum_{i=1}^{n} x_i}{n} = \frac{x_1 + x_2 + \cdots + x_n}{n} \tag{1}$$

where AP_{PC} is Average Precision for Point Clouds model; x_i is Average Precision for each iteration of the building object according to the Point Clouds model.

The value of the average precision of the Mesh model is determined by equation:

$$AP_{MM} = \frac{\sum_{i=1}^{n} y_i}{n} = \frac{y_1 + y_2 + \cdots + y_n}{n} \tag{2}$$

where AP_{MM} is Average Precision for Mesh model; y_i is Average Precision for each iteration of the building object according to the Mesh model.

The value of the average precision of the BOM is determined by equation:

$$AP_{BOM} = \frac{\sum_{i=1}^{n} \omega_i}{n} = \frac{\omega_1 + \omega_2 + \cdots + \omega_n}{n} \tag{3}$$

where AP_{BOM} is Average Precision for BOM; ω_i is Average Precision for each iteration of the building object according to the BOM.

The value of the average precision of the class is determined by equation:

$$AP = \frac{AP_{PC} + AP_{MM} + AP_{BOM}}{3} \tag{4}$$

where AP is general Average Precision of the class; AP_{PC} is Average Precision for Point Clouds model; AP_{MM} is Average Precision for Mesh model; AP_{BOM} is Average Precision for BOM.

The value of the mean average precision (mAP) is determined by equation:

$$mAP = \frac{\sum_{j=1}^{k} AP_i}{k} \tag{5}$$

where AP_i is Average Precision of i class; mAP is mean Average Precision; k is number of defined classes to recognize.

Figure 5 shows the visualization of mathematical processes depicted in (1), (2), (3), (4), and (5) during YOLOv5 work on creating object classification.

The following libraries and software were used in the study: Python 3.8, Numpy, Keras, Tensorflow, Pytorch, json, pandas, CUDA 11.1, and OpenCV 3.2.0.

The YOLOv5 model is trained in the ratio of 80% of training images, and 20% of test images. Images were separated according to the stages of development of simple building things. Table 1 shows the training parameters for the YOLOv5 model.

Comparison according to the FFNN model should be performed when certain standards are defined. The artificial limits that the standard must take into account are shown in table 2.

Table 1. The training parameters to model YOLOv5.

Parameter	Value
Epochs	500
Image size	416
Batch size	16
Training time	42 min

Table 2. Limitation to the instance of class №5 relative to the FFNN model.

	APBO	APPC	APMM	APBOM
Value	0.9	0.9	0.9	0.9

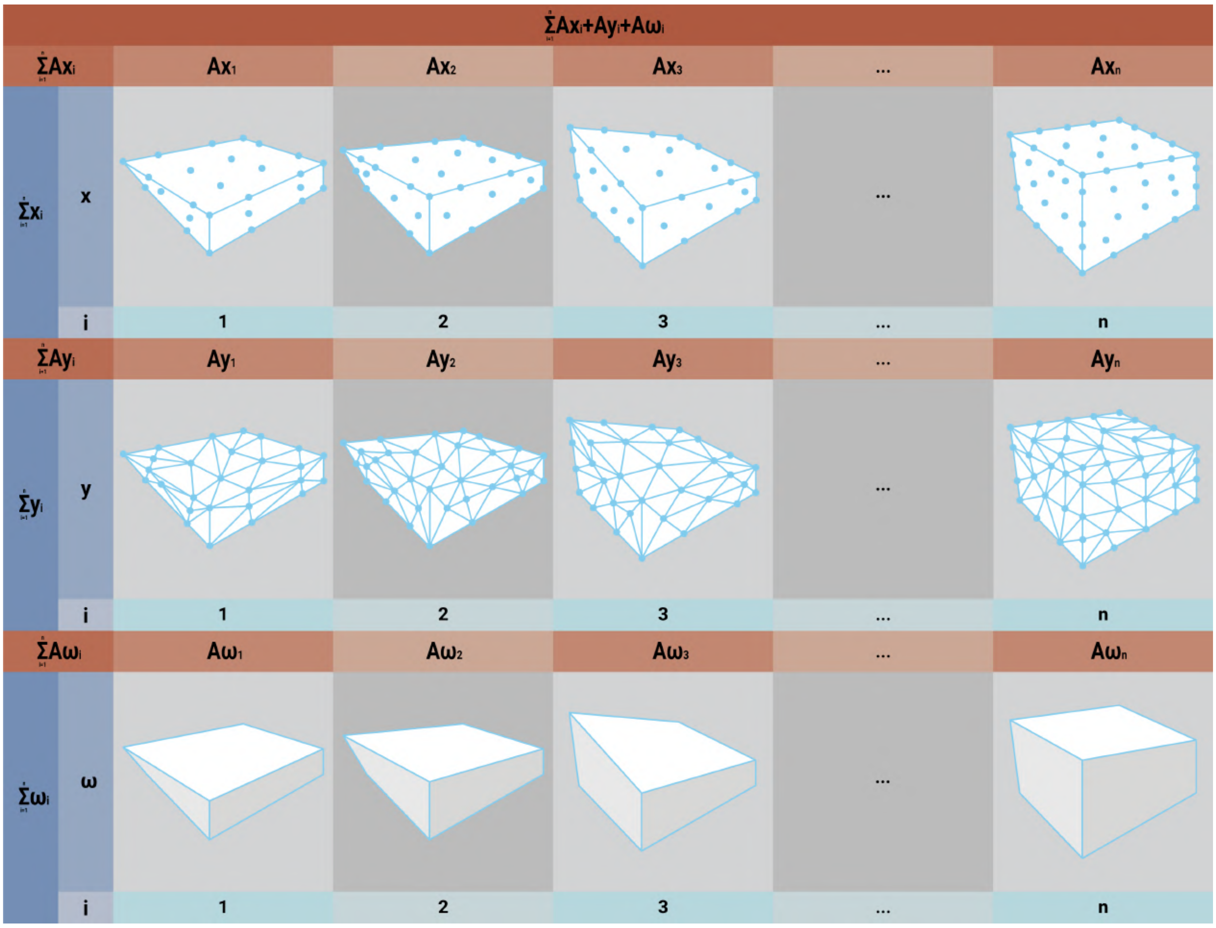

Figure 5. Visualization of mathematical processes about the derivatives of the building object during their classification.

3. Results

Metrics were computed for all classes defined in the Dataset. The maximum Average Precision for the general classification was found for specimen №5 and was 0.88. In general, the YOLOv5 model produced correct classification results for the stated classes and had no discrepancies. However, because some building objects were more difficult to distinguish, the mAP of the YOLOv5 model is 0.73. Figure 6 shows an example of the findings of Instance №5. BO5, BOPC5, BOM5, and BOMM5 are building object, building object (Point Cloud model), building object model (BOM), and building object (Mesh model) in this example, respectively.

Table 3 shows the generalized YOLOv5 classification results by building objects. The indicators range from 0 to 1 and are pre-normalized.

Table 4 shows how the FFNN model works regarding the standards given by the customer based on the building objects. The indicators range from 0 to 1 and are pre-normalized. As a result, the acquired values demonstrate the conformity of classified architectural objects and their derivative models to the required requirements.

4. Conclusion

Thus, the concept of multi-stage modeling of building site objects utilizing artificial intelligence based on BIM technology was proved to be feasible. The classification by time intervals was handled by the information system. The YOLOv5 model displayed an incredibly quick

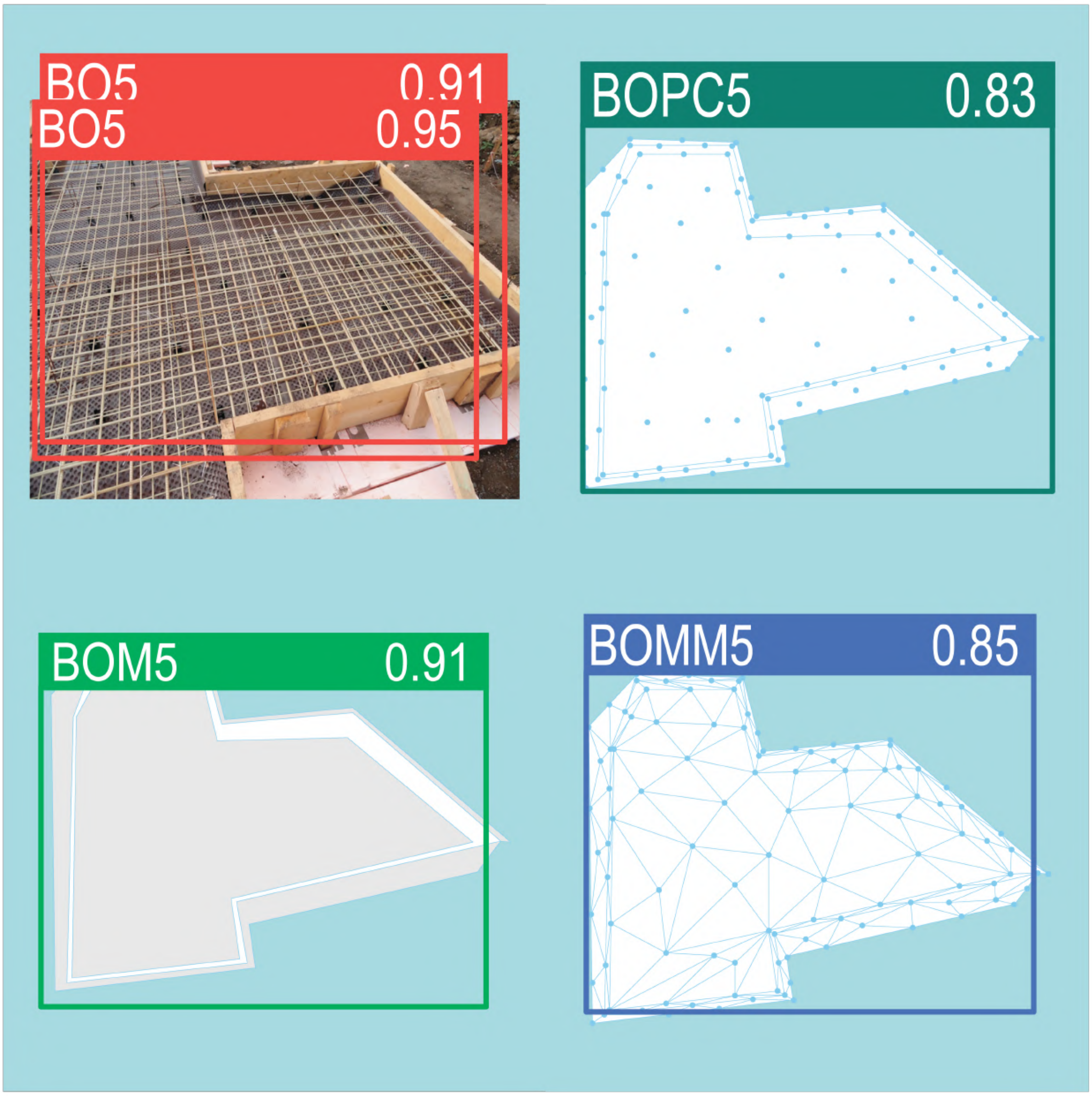

Figure 6. BOM construction is based on photo modeling and SfM classification results based on building objects. The indicators are pro-normalized and range from 0 to 1.

learning process (92 minutes for 500 iterations) as well as a relatively serious mAP of 0.73. Simultaneously, the YOLOv5 model performed classification by the building object's class as well as by its derivative models Point Cloud, Mensh model, and BOM, where it also displayed the related findings. The possibility of establishing quality standards with the help of the FFNN model, which was performed for general indicators by class, was also evaluated, but it can be realized for each stage of the building object's development individually. As a result, the comparison of models and standards based on example No5 revealed a high degree of conformity, ranging from 0.92 to 1.00. The information system model was accurate. Simultaneously, two choices for setting up the building site for photo modeling, static and dynamic, were provided.

The research has implications for the implementation of novel Augmented Reality technologies

Table 3. YOLOv5 model classification results.

Name of the class	APBO	APPC	APMM	APBOM	AP	mAP
BO1	0.79	0.73	0.72	0.79	0.76	
BO5	0.93	0.83	0.85	0.91	0.88	
BO10	0.69	0.61	0.59	0.69	0.65	
BO15	0.86	0.77	0.69	0.81	0.78	0.73
BO25	0.91	0.8	0.77	0.77	0.81	
BO40	0.81	0.68	0.6	0.79	0.72	
BO60	0.69	0.59	0.59	0.6	0.62	

Table 4. FFNN model classification results.

	RAPBO	RAPPC	RAPMM	RAPBOM	RAP
Value	1.0	0.92	0.94	1.0	0.98

for better display of BOMs created at various stages. In addition, the project can be incorporated into cloud storage for working with Big Data and increasing project implementation productivity.

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References
[1] Deng M, Menassa C C and Kamat V R 2021 *Journal of Information Technology in Construction* **26** 58–83 URL https://doi.org/10.36680/j.itcon.2021.005
[2] Hosseini O and Maghrebi M 2021 *Advanced Engineering Informatics* **50** 101378 ISSN 1474-0346 URL https://doi.org/10.1016/j.aei.2021.101378
[3] Mengiste E, de Soto B G and Hartmann T Towards the Integration of Image-Based Appearance Information into BIM *Computing in Civil Engineering 2021* pp 433–440 URL https://doi.org/10.1061/9780784483893.054
[4] Kaiser T, Clemen C and Block-Berlitz M 2022 *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* **XLVI-5/W1-2022** 141–148 URL https://doi.org/10.5194/isprs-archives-XLVI-5-W1-2022-141-2022
[5] Lanzara E, Scandurra S, Pulcrano M, Acquaviva S, Gallo M, Palomba D and Luggo A d 2022 Scan to H-BIM. Image Sampling per reality based Data Mapping *XIX Congreso Internacional de Expresión Gráfica Arquitectónica: 2-4 de junio de 2022* (Cartagena: Universidad Politécnica de Cartagena) pp 523–526 ISBN 978-84-17853-51-8
[6] Demirdöğen G, Diren N S, Aladağ H and Işık Z 2021 *Sustainability* **13**(18) 10029 ISSN 2071-1050 URL https://doi.org/10.3390/su131810029
[7] Sadhu A, Peplinski J E, Mohammadkhorasani A and Moreu F 2023 *Journal of Structural Engineering* **149**(1) 03122006 URL https://doi.org/10.1061/(ASCE)ST.1943-541X.0003498
[8] Baghalzadeh Shishehgarkhaneh M, Keivani A, Moehler R C, Jelodari N and Roshdi Laleh S 2022 *Buildings* **12**(10) 1503 ISSN 2075-5309 URL https://doi.org/10.3390/buildings12101503

[9] Altohami A B A, Haron N A, Ales@Alias A H and Law T H 2021 *Sustainability* **13**(7) 3930 ISSN 2071-1050 URL https://doi.org/10.3390/su13073930

[10] Sezen G, Cakir M, Atik M E and Duran Z 2022 *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* **XLIII-B4-2022** 315–320 URL https://doi.org/10.5194/isprs-archives-XLIII-B4-2022-315-2022

[11] Dolhopolov S, Honcharenko T, Dolhopolova S A, Riabchun O, Delembovskyi M and Omelianenko O 2022 Use of Artificial Intelligence Systems for Determining the Career Guidance of Future University Student *2022 International Conference on Smart Information Systems and Technologies (SIST)* pp 1–6 URL https://doi.org/10.1109/SIST54437.2022.9945752

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Groundwater treatment using polystyrene foam filters with upflow filtration

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Groundwater treatment using polystyrene foam filters with upflow filtration

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Abstract. The groundwater is less susceptible to anthropogenic influence and the water quality of these sources is more stable. At the same time, the groundwater often has an increasing iron concentration. Despite the sufficient availability of proven methods for iron removal from water, it becomes necessary to search for more resource and energy saving technologies which is due to the constant rise in the cost of resources for the construction and operation of water treatment plants. The aeration methods for the iron removal from groundwater are often used, as cheaper ones. The polystyrene foam filters with upflow filtration are of particular interest, as the most reliable in operation among the developed types of filters with floating medium. A further reduction the cost of water is possible by using granules of foam polystyrene obtained by a production method, which ensures an increased grain size in comparison with the traditional method of their obtaining. The positive experience in such filters implementation allowed to recommend the placement of iron removal equipment in the existing water towers.

1. Introduction

The availability of sufficient water amount of adequate quality is one of the main factors of safe living conditions and sustainable development of the state [1, 2]. However, human activity negatively affects the environment, including water resources, which leads to their significant pollution and exhaustion [3–5].

Thus, according to prediction, a half of the world's population will experience water shortages in the near future [6]. The preference is given to groundwater (artesian, springs) underflow when choosing a source of water supply [7, 8].

Groundwater is the main source of drinking water in many countries [9–11]. As a rule, a significant proportion of protected groundwater sources have elevated concentrations of iron, less often hydrogen sulphide, ammonium, manganese, hardness salts, mineralization and other contaminants [12, 13].

Iron content is associated with regional, climatic, landscape and hydrological features. It is known that an increased concentration of iron in water gives it a brownish colour, an unpleasant metallic taste, and causes overgrowth of water supply networks and fixtures [14, 15].

Iron in natural waters can be in the form of ferrous and ferric ions [16, 17], colloids of inorganic and organic origin, which has a significant impact on the choice of method of iron removal.

According to [6] methods of iron removal from water are divided into reagentless, reagent, ion-exchange, membrane and biochemical. At the same time in [18] it is proposed to divide them into four groups: traditional strategies, biological strategies, strategies based on membrane technology and strategies based on nanotechnology.

The preference is given to reagentless (aeration) methods for the iron removal from water because they are relatively simple to operate and easily automated [14, 19]. The most widely used aeration methods include contact iron removal, in which water is fed directly into the granular medium after aeration [6]. In this case the medium grains can have a larger size than in deep aeration. In addition to quartz sand, the other natural and artificial materials are used as a filter granular medium. The type of filtration medium, parameters of its grains and layer height have a significant impact on the efficiency of water treatment, size of filtration units and their productivity. The polystyrene foam is one of the economically suitable medium [6, 20].

The work is devoted to the development of resource and energy-saving schemes of contact iron removal from groundwater at polystyrene foam filters with upflow filtration.

2. Materials and methods

Foam polystyrene filters with upflow filtration have been investigated for a long time in the laboratory of the department of water supply, drainage and drilling at the National University of Water and Environmental Engineering [6, 20].

The plant for studying the iron removal from water consisted of a filtering column, a filtration rate regulator, a piezometer shield and a unit for dosing the iron solution. The filtering column was made of a transparent pipe 150 mm in diameter and 2000 mm in height. A cone was fixed below to it with a branch pipe for connection of aerated water and a washout pipe. A tank of 500 mm in diameter was connected above. It was possible to visually observe the processes occurring in the sublattice space thanks to such construction of the plant. Four branch pipes for the piezometers connection and five samplers were arrange along the height of the filtration column d. The amount of water sampled by the samplers did not exceed 5% of the flow rate passing through the filtration column. The head losses in the filtration column was monitored with the help of the piezometer shield.

The construction features of filters, water treatment efficiency, hydraulic laws of processes in the medium for different operating conditions were studied. The impact of granulometric composition of the medium, layer height, filtration rate, initial water quality parameters (iron concentration, pH, alkalinity, etc.) on these processes was studied. Special attention was paid to investigation of the medium regeneration by different methods. Extensive pilot and industrial production studies were conducted in the water supply systems of a number of settlements of the north-western regions of Ukraine at the introduced plants for iron removal from water with foam polystyrene filters of productivity from 2 to 900 m^3/day.

The polystyrene foam medium can be obtained in the production conditions (plants of producing the polystyrene pellets) and directly at the place of use. As a rule, the polystyrene is foamed by steam in the first case and by water in the second case. The medium amount in the first case is larger and its density and cost is lower. It is advisable to use gravity polystyrene foam filters with increased granule size at the iron removal from water for medium and large consumers (figure 1). The use of industrially manufactured polystyrene foam pellets allows reducing the cost of medium purchase by 4.5 times.

3. Results and discussion

Foam polystyrene filters with upflow filtration can be used in the reagent schemes of water clarification and decolorization, in the schemes of iron removal from water, for water pretreatment.

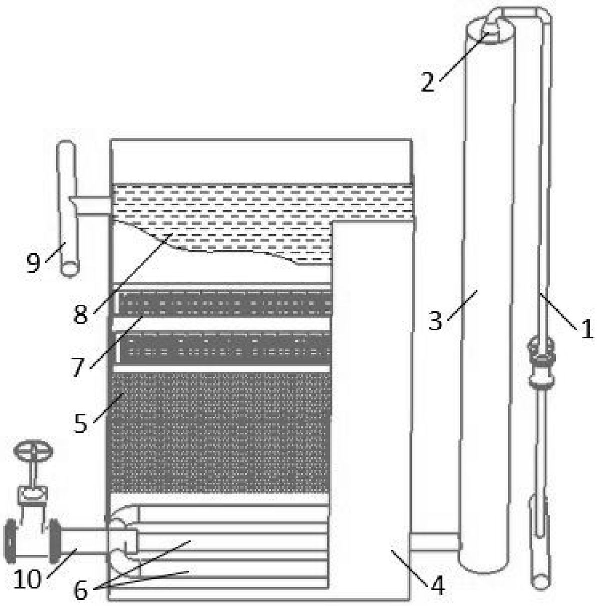

Figure 1. Iron removal from water at the gravity polystyrene foam filters with upward filtration: 1 – the groundwater supply pipeline; 2 – the aerator; 3 – the air separator; 4 – the filter body; 5 – the polystyrene foam medium of industrial production; 6 – the bottom drainage and distribution system; 7 – the holding grid; 8 – the above-filter volume of water; 9 – the pipeline for filtrate removal; 10 – the washout pipeline.

It is recommended to use aeration followed by filtration aimed at removing water treatment from iron ions. It is known that a catalytic film of iron oxides should form on the surface of the medium in order to obtain the necessary effect of iron removal from water, which is not washed off after the filters washout. The catalytic film of iron oxides on the surface of the medium intensifies the adsorption of ferrous iron and its oxidation. Thus, there is no direct contact of the treated water with the surface of the floating medium (polystyrene foam). The ordinary foam polystyrene filters are used at low concentrations of iron ions in the source water and at significant concentrations of iron ions with a growing layer of suspended sediment and foam polystyrene medium. The construction of such filters provides for a sediment layer in the sub-filter space, where the main iron extraction takes place and the final one is directly in the foam polystyrene medium. The sediment layer increases over time, increasing the efficiency of water treatment in it. A part of the sediment is discharged with the washout water. The use of expanded polystyrene filters with a growing sediment layer with each washout of the medium makes it possible to significantly reduce the building area of the wastewater treatment plant. At the same time, the total height of the filtration room will be slightly higher.

We propose the concentration of iron in water after passing the growing layer of suspended sediment $[Fe_l]$ (mg/L) to determine by the equation

$$[Fe_l] = [Fe_0] \exp\left(-\frac{K_1 H_1}{V}\right), \tag{1}$$

where $[Fe_0]$ (mg/L) is the concentration of iron in source water; V (m/h) is the filtration rate; H_1 (m) is the height of the suspended sediment layer; K_1 (1/h) is the coefficient, taking into account the physicochemical parameters of water and contact medium.

The value of the coefficient K_1 was obtained experimentally and is 0.7-2.5 1/h. The studies were conduct at a water temperature of 5-15 $^\circ C$ for the purpose of determining H_1, the concentration of iron in the source water 15-30 mg/L and the rate of upflow of 2.5-4.0 m/h. The following empirical dependence H_1 (cm) was obtained based on these studies

$$H_1 = H_0 + 0.0004V^4[Fe_0]^{1.8}t, \tag{2}$$

where H_0 (cm) is the initial height of sediment layer; t (h) is the duration of water treatment in the growing layer of suspended sediment.

To check the adequacy of the last equation in figure 2 the dependences of the growth of the suspended layer of deposit obtained experimentally were built with points and by straight lines were based on equation (2). It can be seen from figure 2, that the growth rate of the sediment layer calculated by the equation (2) agrees well enough with the data obtained in the process of research, the error does not exceed 15%.

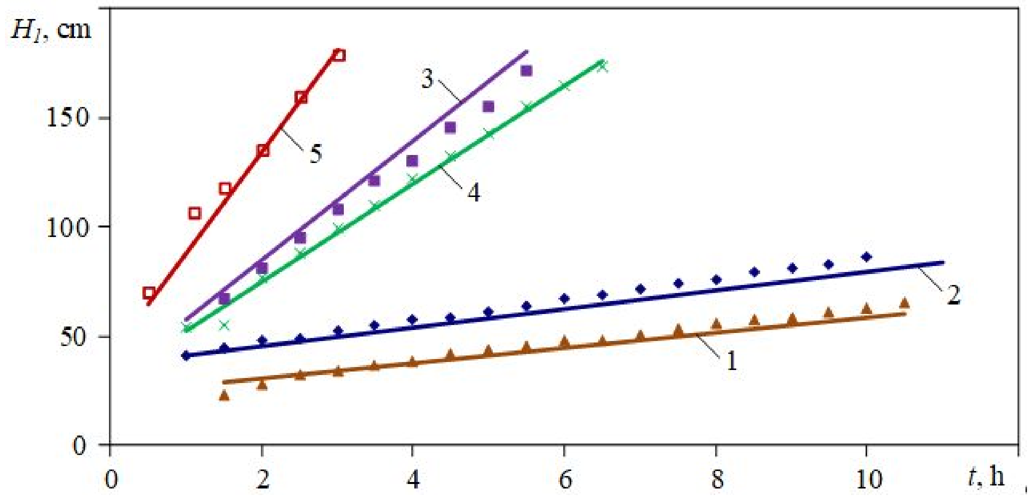

Figure 2. Growth of the suspended sediment over time: 1 – $V = 2.5$ m/h, $[Fe_0] = 20$ mg/L; 2 – $V = 3.0$ m/h, $[Fe_0] = 15$ mg/L; 3 – $V = 3.5$ m/h, $[Fe_0] = 25$ mg/L; 4 – $V = 4.0$ m/h, $[Fe_0] = 20$ mg/L; 5 – $V = 4.0$ m/h, $[Fe_0] = 30$ mg/L.

The peculiarity of the foam polystyrene filters operation with the growing sediment layer is a gradual reduction of iron concentration in the water entering the polystyrene foam medium. We propose the concentration of iron in the filtrate $[Fe_f]$ (mg/L) to determine by the equation

$$[Fe_f] = [Fe_l] \exp\left(-\frac{K_2 L}{V}\right), \tag{3}$$

where L (m) is the thickness of filtration medium layer; K_2 (1/h) is a coefficient considering the impact of catalytic properties of the filtration medium to the efficiency of impurities detention from water.

Coefficient value K_2 is obtained experimentally and is 15-20 1/h.

The concentration of iron in the filtrate during the iron removal from water at polystyrene foam filters with the growing layer of suspended sediment is determined by substituting equations (1) and (2) into equation (3).

The increased sub-filter space is the feature of the foam polystyrene filter with a growing layer of deposit. The height of the sub-filter space H_u (m) to ensure the required initial height of the growing layer of suspended sediment after washout, is

$$H_u = 0.06it_b + h_0, \tag{4}$$

where 0.06 is the transfer coefficient; i (L/(s·m^2)) is the washout intensity; t_b (min) is the washout time; h_0 (m) is the initial height of the suspended sediment layer which depends on the quality of initial water and the upflow rate.

The height of sub-filter space increases with increasing duration and the washout intensity. The washout intensity and duration of polystyrene foam depends on its height and granulometric composition. At the same time, a longer duration and intensity of washout is necessary with an increase in the height and diameter of the grains of the medium. Therefore, it is necessary to accept fine-grained medium to reduce the height of the sub-filter space.

Table 1 shows the results of four gravity filters with polystyrene foam medium obtained in production conditions. The total capacity of the filters was up to 1000 m^3/day. The filtration was conducted by upflow through the polystyrene foam medium with the equivalent grain diameter of 2.8 mm. The filtration rate was accepted as 7 m/h and the medium layer height was 1.0 m based on the results of laboratory tests. The washout of polystyrene medium was carried out by treated water from the combined above-filter space of filters by opening the gate valve on the washout pipeline. Filters are taken for washout alternately once a day with a calculated washout intensity of 18 L/(s·m^2) and a duration of 3 min.

Table 1. Results of the iron removal from water.

Time from the beginning of the filters operation, months	Concentration of iron in the filtrate, mg/L				
	Source water	1 filter	2 filter	3 filter	4 filter
2	1.07	<0.05	<0.05	<0.05	<0.05
3	0.83	<0.05	<0.05	<0.05	<0.05
4	2.88	0.07	0.10	0.10	0.10
5	0.97	0.05	0.06	0.05	0.06
6	1.37	<0.05	<0.05	0.10	<0.05

The semi-annual studies showed satisfactory quality of the filtrate by the concentration of total iron, which did not exceed 0.1 mg/L.

The results of long-term laboratory and industrial studies on the implemented water treatment plants with gravity polystyrene foam filters showed their efficiency, reliability and ease of service [6, 20]. This experience allowed us to recommend the placement of the iron removal equipment in the existing steel water towers and the tower of water iron removal plants for small consumers (rural water supply systems) (figure 3). It allows to avoid the construction of filtering plants and clean water reservoirs, the construction of network pumps and filters body, which significantly reduces building costs in comparison with the previous scheme. We have proposed and implemented a combined medium consisting of small granules of polystyrene foamed with water and large granules foamed with steam to ensure the required efficiency of the iron removal from water and to reduce the cost of the medium. Tower iron removal plants operate in the discrete mode depending on the volume of the tower tank and the mode of water consumption.

Granular filters, including polystyrene foam filters, need periodic regeneration of the medium layer (washout). Reducing the volume of washout reduces the harm to the environment, reduces the size of plants for the water treatment, energy costs for its pumping and the cost of water. The water from the above-filter space is used for the polystyrene foam filters washout. Therefore, the reduction of washout volume will also reduce the total height of the filter. We have tested the impulse washout of polystyrene foam medium, which allows to save 15-40% of washout water in comparison with the continuous water washout.

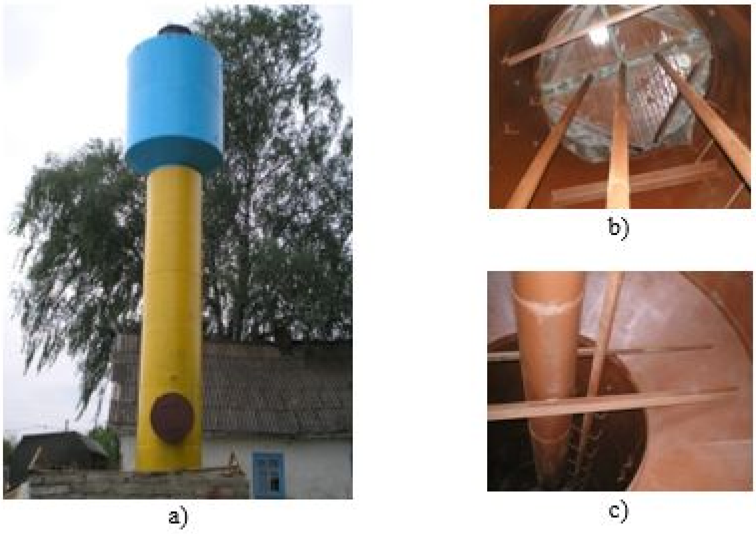

Figure 3. Reconstruction of metal water tower using the polystyrene foam filter: a) the general view of the tower-column; b) the holding grid, pipelines: the inlet water supply (left), the aerated water (centre), the filtrate intake (right); c) the air separator (left) and the inlet water supply pipeline (right).

4. Conclusions

Foam polystyrene filters can be used in schemes for iron removal from water. At a low concentration of iron ions the polystyrene foam filter is used in the source water without a contact mass at the bottom of the filter, and at a significant concentration of iron ions is used with a growing layer of deposit and the polystyrene foam medium. The implementation of contact water iron removal schemes with foam polystyrene filters with upflow filtration allows to reduce building and operation costs during reconstruction of existing and building new water iron removal plants. In addition, the use of tower water iron removal plants in existing rural water supply systems significantly reduces the assembling time. Ease of maintenance of polystyrene filters with upflow filtration makes them competitive in the absence of highly qualified service personnel. It is reasonable to apply mathematical modelling as one of the directions of future studies for substantiation of rational constructive and technological parameters of foam polystyrene filters operation and service life of the medium.

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References

[1] Epoyan S, Karahiaur A, Volkov V and Babenko S 2018 *East.-Eur. J. Enterp. Technol.* **10**(91) 62–69
[2] Klimov S V and Klimova A V 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1049**(1) 012038
[3] Dushkin S and Shevchenko T 2020 *East.-Eur. J. Enterp. Technol.* **4**(10) 26–36
[4] Martynov S, Kvartenko O, Kovalchuk V and Orlova A 2020 *IOP Conf. Ser.: Mater. Sci. Eng.* **907** 012083
[5] Polyakov V, Kravchuk A, Kochetov G and Kravchuk O 2019 *EUREKA, Physics and Engineering* **1**(20) 28–35

[6] Orlov V O 2008 *Groundwater deferrization by simplified aeration and filtration* (Rivne: NUWEE)
[7] Tugai A M, Oleinik A Y and Tugai Y A 2004 *Performance of water wells under colmatage conditions* (Kharkov: KhNAGH)
[8] Stiriba Y, Gourich B and Vial C 2017 *Chem. Eng. Sci.* **170**(12) 705–719
[9] Sharma S K 2001 *Adsorptive Iron Removal from Groundwater* (London: CRC Press) URL `https://doi.org/10.1201/9781003210986`
[10] Maharjan A K, Mori K, Nishida K and Toyama T 2022 *Water Supply* **22**(1) 462–473
[11] Mekhelf Z K, Subhi A D and Hamied R S 2020 *Eng. Technol. J.* **38**(8) 1154–1159
[12] Cheng L, Xiong Z, Cai S, Li D and Xu X 2020 *J. Water Process. Eng.* **38** 101621
[13] Du X, Liu G, Qu F, Li K, Shao S, Li G and Liang H 2017 *Desalination* **403** 97–106 ISSN 0011-9164 Desalination Using Membrane Technology URL `https://doi.org/10.1016/j.desal.2016.03.002`
[14] Nikoladze G I 1987 *Improving the quality of underground water* (Moscow: Stroiizdat)
[15] Sun C, Wang G, Sun C, Liu R, Zhang Z, Marhaba T and Zhang W 2021 *Water Supply* **21**(4)
[16] Chaturvedi S and Dave P N 2012 *Desalination* **303** 1–11
[17] Tekerlekopoulou A G, Vasiliadou I A and Vayenas D V 2006 *Biochem. Eng. J.* **31**(1) 74–83
[18] Khatri N, Tyagi S and Rawtani D 2017 *J. Water Proc. Eng.* **19** 291–304
[19] Galangashi M A, Kojidi S F M, Pendashteh A, Souraki B A and Mirroshandel A A 2021 *J. Water Proc. Eng.* **39** 101714
[20] Martynov S, Kunytskyi S and Orlova A 2017 *East.-Eur. J. Enterp. Technol.* **5/10**(89) 19–26

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Traditional settlements historic experience of “non-detached” preservation (cases of Shirakawa village Ogimachi in Japan and Kryvorivnia village in Ukraine)

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Traditional settlements historic experience of "non-detached" preservation (cases of Shirakawa village Ogimachi in Japan and Kryvorivnia village in Ukraine)

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Abstract. The article concerns of the comparative study of traditional settlements historic experience of "non-detached" preservation. "Non-detached" there is understood like a way to preserve the whole settlement on its original place, with its local traditions, community system, crafts and customs, and in the harmony with natural environment. The cases of the study are mountain Shirakawa village Ogimachi in Japan and Kryvorivnia village in Ukraine. The both settlements are generally showing very similar historical background of geographically isolated life in the harmony with high mountain nature that leads to the shaping of original local architecture style, cultural traditions and community features. Similarly, the initiative of revitalization in the both cases emitting from local communities. Nevertheless, the history of preservation and revitalization efforts of the two cases is quite different. While in Shirakawa village Ogimachi local community took revitalization efforts starting from the middle of 20th century, Kryvorivnia village was engaged in the process starting from the middle of 19th century just with some interruption due to the soviet times. Currently the both settlements achieved good results in their revitalization and local traditions preservation activity also keeping harmony with environment. Shirakawa village Ogimachi is mostly orientated on inner community life that is almost not intersected with flourishing local tourism. Contrary, Kryvorivnia allows tourists to participate freely in local community life, rituals and festivals. Thus each of the two cases examined finally found its original way of historical settlement culture sustainable preservation and revitalization.

1. Introduction

The preservation of traditional settlements in "non-detached" way is an interesting and quite rare experience that could be observed mainly in the territories geographically isolated that lead to the phenomenon of specific local "time delay". It some cases such traditional settlements deny the common way of transferring their old buildings to the "open air rural museums" instead choosing the way of "non-detached" settlement preserving as a core of local architecture, culture and traditional way of living. The current circumstances of world globalization any case have to be took in the consideration there leaving the village community to make a choice between their identity dissolving in the case of fully opening to the world or cultural stagnation in the case of fully closing from it. The original strategies of creative sustainable development and revitalization can help the situation allowing the local communities to find a "middle way" of balancing between these two crisis points. It is due to emphasize that the common receipt for such activities is not exist. Every traditional settlement is looking for its unique way to achieve the balance between the traditional and modern life, cultural stagnation and globalization dissolving often designating the settlement as UNESCO Cultural Heritage [1, 2].

Here is analyzed and compared the unique revitalization experience of Shirakawa village Ogimachi in Gifu prefecture, Japan (UNESCO World Heritage) and Kryvorivnia Carpathian village in Ivano-Frankivsk district, Ukraine. The research was fulfilled basing of personal author field research of the both cases. The research of Shirakawa village Ogimachi case was supported by Grant of Hakuho Foundation Japanese Research Fellowship program 13th (2018-2019). The main methods of the research were "in situ" observation, fixation and interviews.

2. Shirakawa village Ogimachi case

Shirakawa village Ogimachi is one of a group of very interesting deep mountain traditional settlements historically formed on the border of Gifu and Toyama Prefectures. Shirakawa-go is located in a narrow valley of Shogawa river (figure 1).

Figure 1. The picturesque landscapes of Shirakawa village Ogimachi.

Up to the beginning of 20th century this geographically isolated area was really difficult to access. Due to this, here was formed a cluster of settlements with original architectural Gassho-style rural houses and specific social culture [3, 4].

2.1. Historical overview of Shirakawa Ogimachi settlement

Local recordings suppose that the settlement existed here at least from 11th century At the beginning of 21th century the population of Shirakawa village Ogimachi consisted for about 600 people. There for about 60 Gassho-style farmhouses mostly built from early 19th century till early 20th century [4], two Buddhist temples and a Shinto shrine.

The large Gassho-style rural houses of the region are unique in Japan. The name "Gassho" is coming from the image of their high triangle thatched-roofs that are similar with two hands jointed for a pray. The houses are usually face to the north and sous to minimize wind force according to the predominant wind direction of the region (figure 2).

The construction of the houses is extremely strong and spacious allowing to bear local winds and high weight of the snow as well as sheltering big local families [5, 6]. Layout and compositional structure of the houses is perfectly adapted to the local craftsmanship and the way of life. Namely, due to the luck of agriculture grounds the main jobs of the villagers historically was silkworm farming as well as Japanese paper (washi) and nitre for gunpowder manufacture. Thus the houses have wide working spaces in a ground floor as well as multileveled roofing spaces used for silkworm nests and their food (mulberry tree leaves) storage. These spaces due to the original roof construction are properly ventilated and disinfected with open

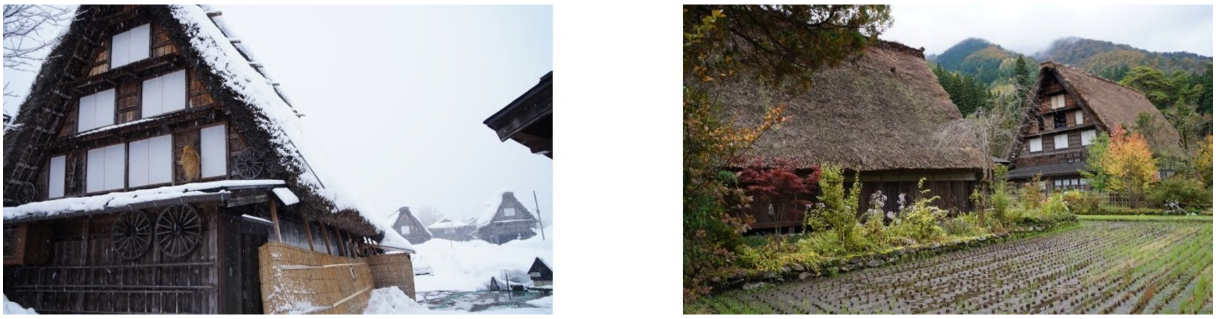

Figure 2. Gassho-style rural houses.

domestic fireplace smoke freely penetrating all roofing joints and creating perfect environment for silkworms breeding.

It have to be noted that from the beginning of 20th century the quantity of Gassho-style houses of the area significantly diminished. As for 1924 there were for about 300 such buildings in the region while by 1961 they were already only 190 [4]. This situation arose due to the nearby construction of hydroelectric power plant on Shogawa river at the beginning of 1940th that led to waterlogging and abandoning of several small villages of the area. Some houses also were lost by fires or reselling [4,6]. Finally facing with this problem the residents of Gassho-style dwellings of Shirakawa village Ogimachi started a movement to protect the houses of the settlement. They concealed the three principles of "Do not sell", "Do not rent", and "Do not destroy" in 1971 establishing the "Association to Protect the Natural Environment of Shirakawa-go, Ogimachi Village" starting in the village different preservation activities. These efforts lead to further selection of the area as a district for the protection of nationally important traditional buildings in 1976 [4].

Finally there shaped very interesting form of traditional rural settlement preserving directly at the place, without usually implemented in such cases museification or "open air rural museum" creation. The habitants of the village are living at theirs houses and at the same time serving as the caretakers for them.

In 1995, Shirakawa village Ogimachi together with neighboring settlements were registered as the UNESCO World Heritage Site as the "Historic Villages of Shirakawa-go and Gokayama" by following criterion [5]:

Criterion (iv): The Historic Villages of Shirakawa-go and Gokayama are outstanding examples of traditional human settlements that are perfectly adapted to their environment and their social and economic raison d'être.

Criterion (v): It is of considerable significance that the social structure of these villages, of which their layouts are the material manifestation, has survived despite the drastic economic changes in Japan since 1950. As a result they preserve both the spiritual and the material evidence of their long history.

UNESCO World Heritage site is consisting of three locations as Shirakawa village Ogimachi in Gifu Prefecture and neighbor villages Ainokura and Suganuma in Toyama Prefecture together forming 68 hectares of preserving area surrounded with buffer zones [5].

2.2. Modern situation of Shirakawa village Ogimachi preservation and revitalization, community and touristic activities

The management and daily preservation activity of Gassho-style rural houses is the responsibility of the owners. More complicate restoration works are held by professionals. Special attention is given to the use of traditional materials [4, 5, 7].

The thatched-roofs of the local houses require the replacement every 20-30 years. Nowdays it is extremely valuable proses (for about more than 10 million yen, or approximately 75000 dollars costs only to replace one side of the roof) must be done by villagers themselves [4]. For this situation there exist traditional local community called yui, that accumulate the money from all households to allow roof replacements of 2-3 houses a year. It takes for about 200 or even more workers and up to 100 of them could climb on the roof at once. One side of the roof replacing usually takes 2 days of the work. The work is divided among all yui community participants depending of their age, sex and qualification. So, while young men are directly engaged in the process on the roof, senior people supervise the work, teenagers and women are preparing grass bundles on the ground or serve the meals to other participants. After the work is finished, the owners of the house prepare a feast called naorai for all who was engaged in the process. Old village records proving that the tradition of yui existed there at least from the end of 18th century [4]. So it can be cleared that traditional dwelling maintaining techniques of Shirakawa Ogimachi settlement are carefully transferred to the new generation (figure 3).

Figure 3. The roof replacement in Shirakawa village Ogimachi.

Accustomed to live in tight close community from the ancient times, the habitants of Shirakawa village Ogimachi are still preserve strong community relationship not only in the field of yui roof replacement activity but also in the traditions of daily social life as well as annual festivals, weddings, funerals and so.

Traditional manufacture of the settlement (silk-worms farming, paper and gun-powder production) is abandoned now. Instead, almost all habitants are engaged in tourism activities holding in their Gassho-style buildings architectural and folklore museums, cafes, souvenir shops or guesthouses They are still preserving natural way of life in accordance with the nature including local agriculture and cuisine based on self-cultivated cereals and vegetables, forest plants and mushrooms. The old settlement traditions are studied in local schools that itself also is a very interesting example of tradition preservation activity.

This extremely picturesque place quickly gained the attention of domestic and foreign tourists, but from 2008 when a new Tokai-Hokuriku Expressway was constructed nearby making smooth access to the area, the touristic overgrowth of the settlement became a problem. Most of the tourist are visiting there by guided buses or private cars for a day returning trip and thus not are so useful for local economic. Recently due to coronavirus disease the situation changed a little but with world recovering from the epidemic this problem intends to return.

3. Kryvorivnia case

Kryvorivnia village is located in the deep forestland Carpathian mountains of Ivano-Frankivsk district at the valley of Black Cheremosh river. This territory is historical place of Hutsul Ukrainian ethnic subgroup habitation preserving till now their original wooden building technics, crafts, traditions and local dialect. The village has typical for the area dissolved urban structure of small and sometimes quite separated with the mountain landscape clusters of rural houses.

3.1. The history of Kryvorivnia settlement

Kryvorivnia village is known from the historical records from 18th century but the real age of the settlement could be much more ancient. From the middle of 19th century and so on, Kryvorivnia became popular as a natural resort and finally get attention of the famous cultural personalities often being visited by Ukrainian writes, historians and artists of the time as Ivan Franko, Lesya Ukrainka, Mykhailo Hrushevsky and others [7]. In 1910-1911 Mykhailo Kotsiubynsky who lived there for a while, wrote his famous based on the local Hutsul people legends and traditions novel "Shadows of Forgotten Ancestors" ("Wild Horses of Fire"). Later, in 1964, a famous Sergei Parajanov filmed this novel at the same place at Kryvorivnia [8].

During the dark times of the Second World War and further soviet occupation the cultural life of Kryvorivnia village significantly declined. Until the end of 20th century it remained just one of the calm and lovely sightseeing but not outstanding villages of Ukrainian Carpathians.

3.2. Kryvorivnia village tradition preservation, modern revitalization activity and community life

New period of Kryvorivnia village culture flourishing started at 1995 with a young priest Ivan Rybaruk obtaining parish at local wooden Virgin Mari's Nativity church. The cultural and revitalization efforts of the new priest were willingly supported by local community that quickly started to restore old traditions, religious and community life and indigenous folk festivals of Kryvorivnia. The most notable of such festivals are the cycle of winter religious celebrations of Orthodox Christmas, the same as spring Easter festival and summer "Sheeps sending to poloninas" festival attracting many domestic and foreign tourists and guests.

There are still flourishing the tradition of so called "kolyadka" an ancient folklore Christmas songs the same as local musical bands performing with violins and "trembitas" – extremely long Hutsul trumpets fabricated from the wood of the trees striked by the lightening. At the day of Baptism that is celebrated there at 19th of January, local community and the guests praying on the bank of Black Cheremosh River near erected in the water big decorated Cross made of the river ice. "Sheeps sending to poloninas" festival took place in Kryvorivnia in June. In this day the villagers sanding their sheeps to the upper mountain pastures (so called poloninas) for all of the summer (figure 4).

A very special feature of Kryvorivnia culture is the tolerance to the other religions, nationalities and ways of living. Significant Orthodox services are sometimes held there together with Catholic and Greek Catholic priests. The people of any other religion also allowed to

Figure 4. Christmas and Baptism annual festivals in Kryvorivnia.

Figure 5. Maria's Nativity wooden Church of Kryvorivnia: metal leafs covered exterior, the original exterior after the restoration at the end at 2010th, interior.

come and pray in the local Maria's Nativity Church that is the center of community life and revitalization activity (figure 5).

This wooden church is supposed to be built in nearby place in 17th century and then relocated to Kryvorivnia grounds in 1719. It is a good example of local Hutsul architecture style. The wooden log church has cross-shape layout and one central opened to the interior and lightened with windows massive octagonal dome-tower. In the soviet times it was registered as National Cultural Property, but as it was then usual, nobody of the officials cared about the situation on the place. As a result, by 1980th the top of the church decayed and the dome-tower and the walls were covered with metal leafs as a recent cheap but harmful for the wooden structure repairing method. At late 2010th, due to community efforts, local carpenters repaired Maria Nativity church recovering its original exterior covering the walls and tower with chopped wooden planks as it was there traditionally accustomed for rain penetrating preventing.

A huge amount of 200-100 years old rural dwellings are still in use in Kryvorivnia, but in this case we can speak not only about old architecture traditional maintenance skill preserving. It is notable that local building carpenters are still preserving and passing to the new generation their skill to build new traditional rural houses, chapels and churches. Building customs and dwelling evil defence pre-Christian traditions also are still in use.

Other traditional crafts, manufacturing and arts such as agriculture skills, sheep breeding, cheese making, carpets making, wood curving, egg painting (pysanka art), and so also are flourishing. In this case it is quite natural that Kryvorivnia obtained a great popularization as a place of mountain green-tourism, sightseeing, hiking and skiing, mostly attracting single travellers, small groups of friends and families who can easily settle in the villagers dwellings or small house-hotels closely communicating with local habitants and fully participating in their life activities.

There is also significant museum activity that permanently has a tendency to increase. On the moment at Kryvorivnia functioning 7 museums of different types. Such as of literature and art celebrities memorizing museums, ethnographic and historic museums, the museum of local dwelling of 19th century "Hrajda" – Hutsul type rural house with inner yard operating by the family of its owners, and "Didova apteka" ("My grand-father's pharmacy") museum created by local Zelenchuk family for the memory of their grand-father, famous local herb healer [9]. Recently there opened also a museum of repressed by soviets local talented female artist, ethnographer and writer Paraska Plytka-Horytsvit (1927–1998) whose significant heritage is now carefully classified and popularized by the local community [10].

At recent 20 years Kryvorivnia also fully reobtained its historic significance as an "artistic hub" of Carpathians often being visited by writers, artists, actors, photographers, filmmakers and other representatives of culture. In this meaning, Kryvorivnia village could fully reobtain its historic function as artistic hub and "cultural capital" of the Carpathians.

4. Comparing the cases

The two cases of traditional settlement “non-detached” preservation and revitalization examined there have very similar initial geographic circumstances both being located in the deep mountain forest regions historically hard to assess and due to this almost fully preserving their original building skills, customs, way of living and social relationship. The both are steel deeply integrated to natural surroundings. Their revitalization activity is the result of local community efforts and the way of this activity is mostly inspired by local habitants decisions sowing the diversity of original revitalization methods.

In Kryvorivnia community we can observe stronger religious component than in Shirakawa Ogimachi case. Due to the personality of local priest, the religious community of Kryvorivnia consolidated around ancient wooden church finally becoming the driving force of local preservation, revitalization and cultural activity. At the same time, in Shirakawa Ogimachi case can be observed stronger cooperation of the local community with prefectural authorities and central government significantly helping in old Gassho-style houses and surrounding territory preservation process and integrating the efforts of the community with Japanese law and UNESCO World Heritage programs.

At figure 6 it is shown the difference between functional abilities of these traditional settlements and the situation with their different traditional activity components preserving. Summarizing the results of figure 6, we can state that functional diversity of Kryvorivnia settlement case is richer and having longer traditions of conscious local cultural activity than Shirakawa Ogimachi case. The approach to traditional building skills preservation also is different. Shirakawa Ogimachi is preserving bigger than Kryvorivnia amount of originally shaped ancient rural houses. While the local artisans of Shirakawa Ogimachi are concentrating their building skills mostly on the maintenance of the Gassho-style houses, living big reparation works to the restoration specialists, Kryvorivnia’s artisans are able to repair, and even rebuild local architecture in the traditional way. There is also still flourishing the tradition of ancient building methods transferring to the next generations. Kryvorivnia building carpenters are not only erecting new diverse rural structures of traditional techniques on the territory of the settlement but also spreading their skills to the wide neighboring area.

The approach to touristic activity organization at Shirakawa Ogimachi and Kryvorivnia also are basically different. While Shirakawa Ogimachi community rather considering the tourists as a passive spectators allowed to observe local life, in Kryvorivnia the tourists and guests fell themselves fully involved in the process of local life including participation in religious services, festivals preparing activity, crafts and local cuisine dishes fabrication and so (figure 7).

The reasons of such difference are probably nestling in the history and culture of the both settlements as well as in the different mentality of their habitants. In Japanese history rural settlements were practically closed social systems with strong local community consolidation not allowing to the strangers to enter in or to the members of communities to go out. While the Ukrainian Carpathian settlements historically had quite open social structure where people settled around separately in small family groups with free coming in and out and consolidating only in the case of practical or defense needs (figure 8).

In general it can be stated that Kryvorivnia traditional settlement is much more that Shirakawa village Ogimachi integrated in the modern world and directed rather to the future development in the harmony with their traditions and surroundings than to stagnation like an artificially limited reserve of traditional life style.

5. Conclusions

The main problem for historical settlement with traditional way of living now is to consider the appropriate proportion between local traditions stagnation and modern life integration. At the cases examined it can be seen that for each historical settlement this question can

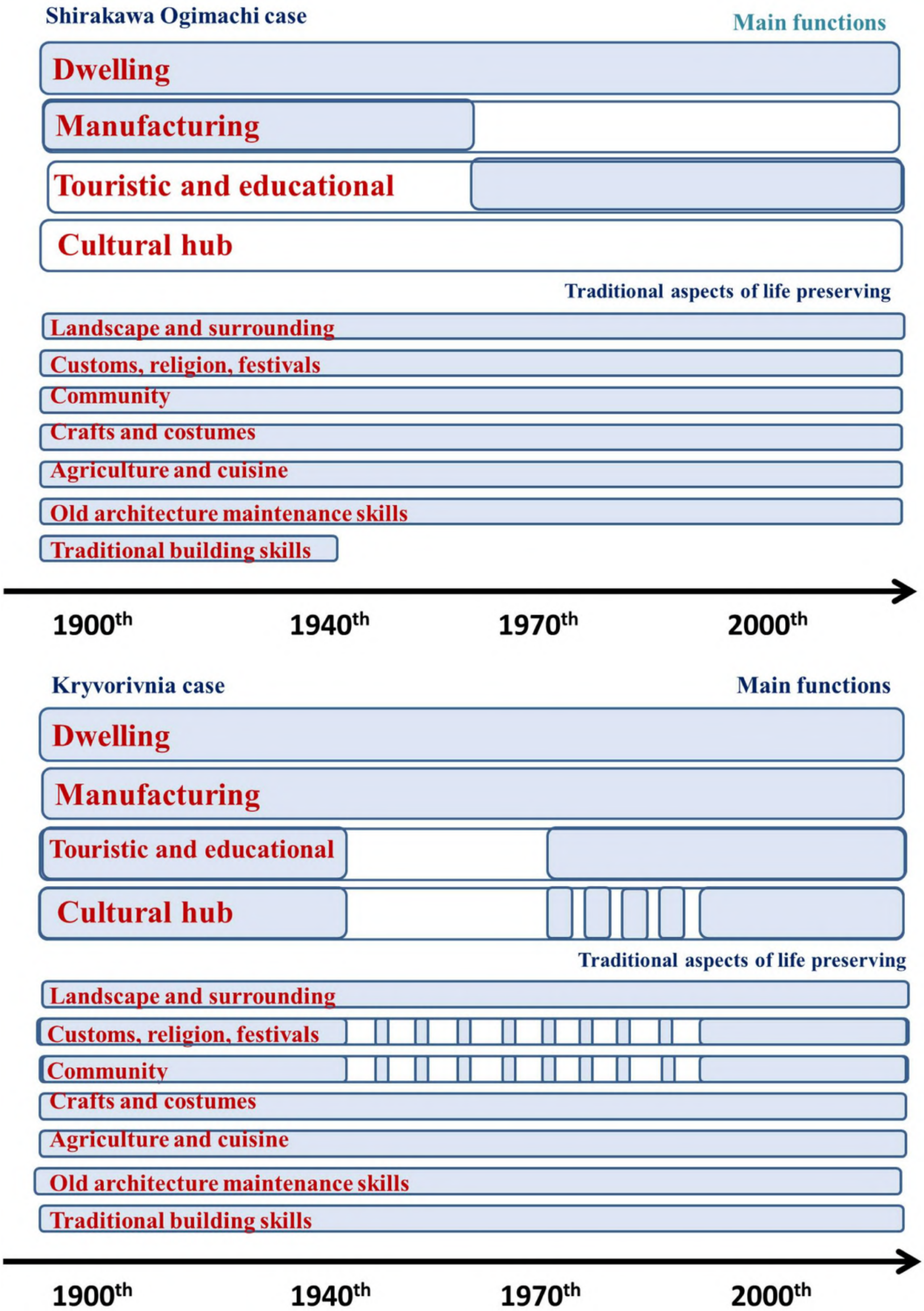

Figure 6. Shirakawa Ogimachi and Kryvorivnia cases functional abilities and traditional activity components preserving (by author).

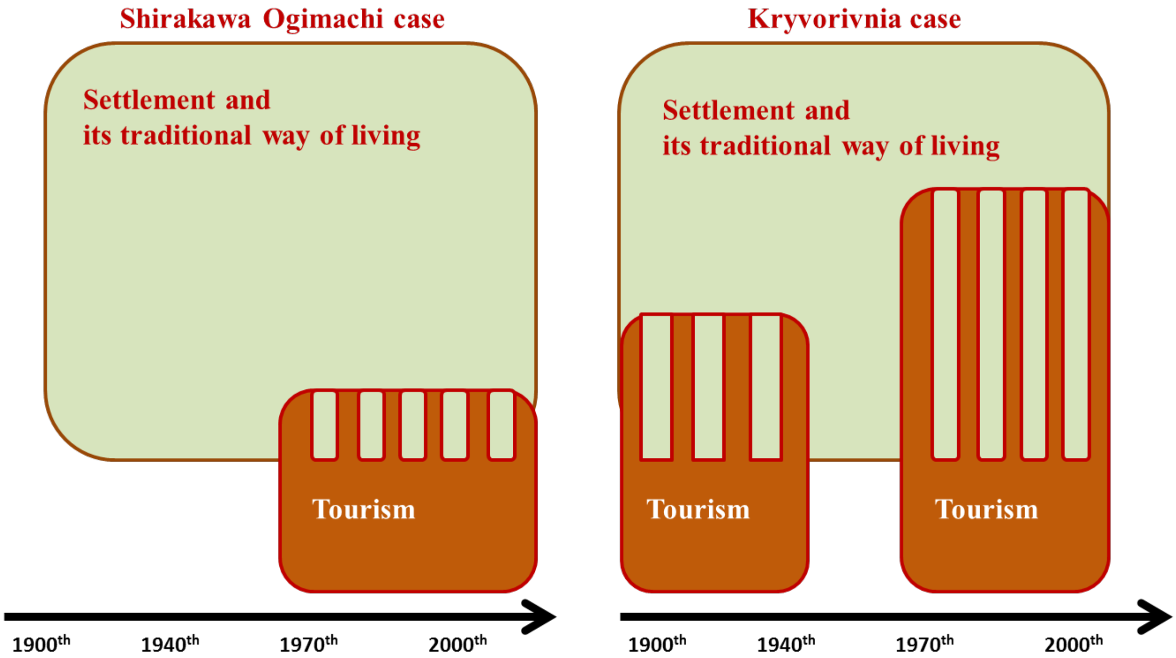

Figure 7. Local life and touristic activity interaction at Shirakawa Ogimachi and Kryvorivnia cases.

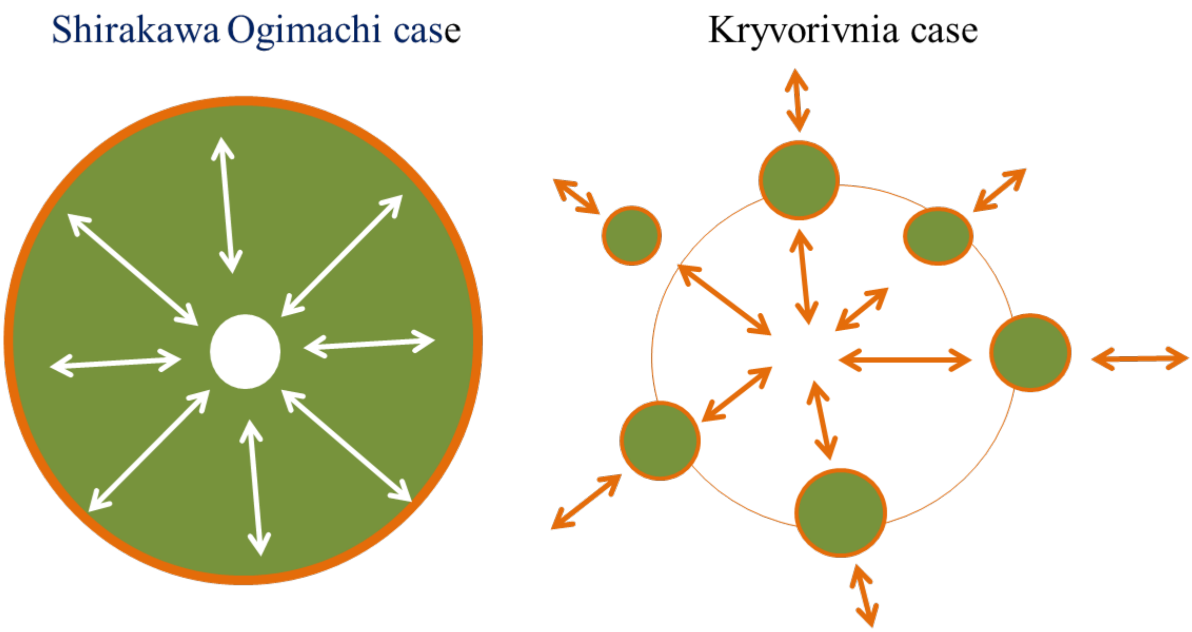

Figure 8. Traditional settlement structure of Shirakawa Ogimachi and Kryvorivnia.

have deferent answers. The “non-detached” preservation of the settlement is possible now only in coexistence with surrounding nature that shape both possibility and necessity to practice continually traditional way of living, customs, building technics, crafts, agriculture and social relationship. From the one hand, the complete stagnation of the local traditions and the way of living in the ancient "status quo" usually leads to the settlement life conservation or museification existing separately from the real word. From the other hand, the excessive openness to the word could lead to the settlement identity dissolving. The decision of desirable proportion between this two crisis points are usually made by local communities and generally reflecting deep national mentality and historical background of the settlement. The same could be applicable also for the question of touristic activities separating or engaging on the local community life of the settlement. Revitalization methods of historical settlements with traditional way of life often are the original products that can lead the local communities to unique domestic heritage preservation and revitalization methods and sustainable development strategies creating.

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References

[1] Kakiuchi E 2012 Sustainable Cities with Creativity: Promoting Creative Urban Initiatives – Theory and Practice in Japan *Sustainable City and Creativity Promoting Creative Urban Initiatives* ed Baycan T, Girard L F and Nijkamp P (Oxford: Ashgate Publishing Limited) pp 413–440

[2] Rezig N H and Shevtsova G V 2022 *IOP Conference Series: Earth and Environmental Science* **1049** 012077 URL https://doi.org/10.1088/1755-1315/1049/1/012077

[3] GOKAYAMA-INFO GOKAYAMA SAISAIGOKAYAMA Official Travel Guide URL http://www.gokayama-info.jp/en/gokayama.html

[4] Shirakawa village office 2016 What Kind of Place Is Shirakawa-go?/Shirakawa Village Official Website english URL https://www.vill.shirakawa.lg.jp/1539.htm

[5] 1995 Historic Villages of Shirakawa-go and Gokayama URL https://whc.unesco.org/en/list/734/

[6] Singh R P B 2019 Continuing culture and meeting modernity: The World Heritage villages of Shirakawa-Gō and Gokayama, Japan *Routledge Companion to Global Heritage Conservation* ed Bharne V and Sandmeier T (Routledge) pp 128–151 URL https://www.researchgate.net/publication/315836219

[7] Kuroda N, Shimomura A, Ono R and Kumagai Y 2001 *Landscape Research (Journal of the Japanese Institute of Landscape Architecture, Ser 19)* **64** 759–764

[8] Sklyarova V 2017 Kryvorivnya: Journey to Origins URL http://web.archive.org/web/20180210074359/http://kharkivobserver.com/kryvorivnya-travel-to-origins/

[9] 2023 Museum "Didova apteka" URL https://didovaapteka.info/en/

[10] 2019 Paraska Plytka-Horytsvit. Overcoming Gravity URL https://artarsenal.in.ua/en/vystavka/paraska-plytka-horytsvit-overcoming-gravity/

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Town-planning tasks and principles of restoration of urbanized territories of the Luhansk region, destroyed as a result of hostilities

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Town-planning tasks and principles of restoration of urbanized territories of the Luhansk region, destroyed as a result of hostilities

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Abstract. The war in Ukraine has led to large-scale destruction. The scale and nature of changes in the urban planning parameters of the Luhansk region under the influence of hostilities and the restoration of urbanized territories are studied. The purpose of the study is to determine the models and principles for the restoration of urban areas affected by hostilities. Theoretical and empirical methods of system and statistical analysis, analytical comparisons, urban planning analysis were used for the study. The paper considers the quantitative and qualitative nature of the impact of destruction and the socio-demographic and economic consequences caused by them on the change in the urban planning parameters of the Luhansk region. The information base consists of literary and archival sources, cartographic materials. The analysis of urban planning tasks for the restoration of urbanized territories destroyed as a result of hostilities is carried out. It is established that the war changed certain functions of the region. The task arises to determine how the change in functions affects the transformation of the territorial typology of the use of territories. The region is at the beginning of the phase transformation of the urban form. A methodology for assessing and making urban planning decisions is proposed. The urban planning tasks and directions for the restoration of the urbanized territories of the Lugansk region, destroyed as a result of hostilities, are analyzed. From the intermediate conclusions, it is advisable to single out that the region has significantly changed its functions. The military and special nature of the use of the territories will be a priority. So, the planning frame of the territory should undergo changes. It is necessary to revise and update general layouts, regional development schemes aimed at the advanced development of programs and projects that primarily ensure the structural growth of territories. The region will experience a labor shortage. So, recovery programs will face a shortage of builders. It is advisable to create and strengthen the departments of the chief architect of the city, expand the staff, to develop current and future tasks for the development of cities.

1. Problem statement

The hybrid intervention of Russia in early 2014 led to an armed conflict known as the ATO/JFO [1, 2]. On February 24, 2022, an open war began. In combat operations, all types of weapons and combat arms are used. Appropriate are the scale and consequences of the destruction. The use of heavy weapons, aircraft, missile strikes in highly urbanized areas for many months leads to large-scale destruction of populated areas to the state of 'scorched earth'. The war is not over yet.

‘Wars begin when you will, but they do not end when you please’ – Niccolo Machiavelli

We also do not set ourselves the task of guessing the date of the end of the war. The fundamental point is the fact that after the end of the war, restoration begins, aimed at eliminating the consequences of hostilities, restoring populated areas, territories abd urban planning systems. Unfortunately, there is every reason to assert that the scale and nature of the destruction of individual urbanized territories is so significant that questions arise as to what and how will have to be restored? The destruction of an individual house is not a problem of its restoration. The destruction of 70% of the housing stock, engineering systems for the city, road and transport infrastructure, raises the question – in what sequence, in what volumes is it necessary to restore the city? There arise the tasks of assessing and determining the scope of work, the order of renewal, the forecasted terms of restoration, sources of financing, the availability of labor resources and the urban development base. And all this in a region that was in decline even before the hostilities. In fact, the question arises of developing a regional program for the development of the territory (region), in parallel with the development of general layouts for the development of settlements for the post-war period. For a detailed analysis of the situation, the development of rational urban planning solutions, it is necessary to solve a number of scientific problems:

- to give a quantitative and qualitative description of the extent of destruction;
- develop a methodology for assessing the impact of the nature of destruction on the state of objects and the possibility of their restoration;
- develop a classification of urban objects and systems according to certain typological features; propose principles and models for the restoration of disturbed urban areas aimed at their sustainable development.

A comprehensive analysis will make it possible to develop options for the long-term and advanced development of the Sievierodonetsk-Lysychansk agglomeration, the functional and planning structure of the settlement.

2. Purpose, idea and research methodology

2.1. The goal of the research

Study of the impact of the scale and nature of destruction as a result of hostilities in the Lugansk region on the possibility of restoring urbanized territories. Determination of models and principles for the restoration of urbanized territories destroyed as a result of hostilities.

2.2. The idea

The armed conflict in eastern Ukraine continued in the worst possible way. Various possible scenarios were predicted, but a full-scale military invasion was considered the most frightening, and therefore hypothetically less likely [3–5]. The totality of internal and external factors, the unpredictability of the modus operandi of the Russian leadership led to the fact that a large-scale war is taking place on the territory of Ukraine, in the east of Europe, with a scale of destruction that the continent has not known since WW2. The use of heavy weapons leads not only to the destruction of individual objects, but also to the destruction of territories. Individual settlements were wiped off the face of the earth. This turns the consequences of the war into a systemic problem that will take years to resolve. The hostilities resulted in the evacuation of the population, the cessation of economic activity, and the paralysis of the housing and utilities sector. It becomes obvious that in the event of the end of the war, complex methodological tasks will arise, covering the priority of restoration, the list of objects subject to and not subject to restoration, approximate time for the implementation of programs and plans for restoration, the definition of the town-planning base for the development of territories, and many other issues. The tasks of updating the general layouts of settlements will become relevant. Regional development programs will have to be radically revised. The new functions of the regional typology are becoming a reality and require taking into account the tasks of improving the territorial planning organization of the Luhansk region and urban development.

2.3. Methodology

Theoretical and empirical methods of systemic and statistical analysis, analytical comparisons, urban planning analysis were used for the study. The paper considers the quantitative and qualitative nature of the impact of destruction and the socio-demographic and economic consequences caused by them, the change in the urban planning parameters of the Luhansk region. The information base consists of literary and archival sources, cartographic materials.

3. Results

An analysis of the scale of destruction indicates a potential change in individual functions and forms of the region. The evolutionary gradual nature of urban transformations has been replaced by an abrupt transition to a new quality. The transformations are in the nature of phase shifts. Post-war restoration will lead to changes in the planning framework of the territory. Recovery tasks are defined, which should take into account changes in the nature of the region's functions. The basic principle is to update and revise general layouts for populated areas and regional development schemes. Anticipatory reconstruction is the priority model of reconstructive restoration. It is advisable to create vertically integrated departments of architecture and urban planning of cities and the regional administration. A classification of construction and infrastructure facilities according to typological features is proposed in order to form post-war reconstruction programs. It is expedient to give priority in restoration to urbanized cells with the maximum development potential.

It is still impossible to make a comprehensive assessment of the consequences of the war. The war is not over yet, the scale of losses and destruction cannot be correctly calculated. Secondly, there is hardly a methodology that allows modeling the volume of losses in a single indicator. Officials give a variety of information, which ultimately allows us to draw conclusions - the scale of destruction is colossal.

"Since Russia's full-scale invasion of Ukraine, the invaders have completely destroyed six cities. This was announced by Deputy Head of the Office of the President of Ukraine Kyrylo Tymoshenko in a video message to the participants of the forum 'Revival of Ukraine –- Revival of Communities' The Donetsk and Lugansk regions suffered the most. There, some cities were destroyed very badly. These include Mariupol, Volnovakha, Rubizhne, Popasna, Liman and Sievierodonetsk. *'According to our preliminary estimates, more than 350,000 objects and millions of square meters of residential, educational, medical, and sports infrastructure have been destroyed in the country, thousands of kilometers of roads and railways, airports, ports, and much more have been damaged. Some of these facilities can be restored, some have been destroyed to the ground'* – Tymoshenko said. The number of damaged and destroyed housing in Ukraine is close to 35 million square meters. Even with a relatively calm economic and social situation, it may take a long time to restore it." [6]

"In Sievierodonetsk, Luhansk region, 90% of residential buildings were damaged as a result of hostilities. This was announced by the head of the regional military administration Sergei Gaidai *'... 70% of the houses destroyed by the Russians are not being restored. In addition, the critical infrastructure of the city is completely destroyed ...'* In addition, the so-called 'LPR' stated that they were not going to restore Popasna: the city was completely destroyed." [7]

It is appropriate to point out that a city is not an arithmetical aggregate of residential buildings. Definitions and criteria of cities in the scientific community differ. What is common is a certain number of the population, mainly engaged in non-agricultural activities, the compactness of the settlement, anthropogenic transformation of the territory. The main functional zones of the city include rural, industrial, landscape and recreational. The defining characteristic of a city is the list of functions and services it provides. Functions of the city are the main types of activities performed by its residents. The main groups of functions are distinguished – city-forming (specialized, exogenous), which determine the economic base of the city. These production functions are industrial production, construction, transport, higher education institutions, tourism and sanatoriums. City services (endogenous) are functions of the city, performed exclusively in relation to its population [8].

Figures 1 and 2 show a panorama and a bird's-eye view of the Popasna district. Figure 3 shows, what the village of Novotoshkivka turned into. The first question that arises is what functions and services inherent in the city are possible? How to estimate the scale of destruction? How should the program for reproduction of these settlements look like?

Figure 1. Panorama of the city of Popasna (population 19,199 people on January 1, 2022) of the Luhansk region [9].

Traditionally, war losses are calculated in monetary terms. But it is possible to argue that any estimates are not final, money has its value, which is determined by the discount rate, and the value of money (as a category) changes over time. Inflationary processes, an integral part of the economy, also contribute their share and are not subject to correction. That is, we can only talk about forecast indicators and program targeting – therefore, any sums of losses are indicative and fix concrete facts for a certain period of time.

Methodologically, these circumstances are taken into account in various methods of real estate valuation, when, depending on the conditions, the object, and the impact factors, the cost method, income method, and comparative method are used [12].

The basis for the financial assessment is the cadastre (registry) of objects that have been destroyed and need to be restored. And in this case, the problem has no methodological support. An attempt to apply an inductive approach (methods of induction and deduction) forces us to develop certain classifications according to certain criteria (features). For example:

Figure 2. Photo of the destruction of a residential building in the city of Popasna, Luhansk region [10].

completely destroyed; partially destroyed; (not) suitable for restoration. But this method gives errors in assessing systems, territorial entities. It is also problematic to determine the degree of destruction of an object and assign it to a certain category. The method of expert assessment seems to be the most adequate, when a qualitative (determining) conclusion is made on the basis of an integral assessment of the amount of identified defects. The list of defects is determined by the methodology, the presence and significance – by experts, the degree of influence of defects on the general condition – by a qualimetric assessment.

It is important to evaluate the final resource of the restoration object and its residual value, since these parameters influence the decision on the feasibility of restoration or replacement. This is also a difficult methodological task, given the fact that there is no real experience of restoring objects destroyed as a result of hostilities in Ukraine. The residual value should also reflect the usefulness of the object – the ability to provide a certain function of urban planning activities.

The primary classification of objects holding destruction as a result of hostilities according to typological features may include:

- Individual residential houses;
- Multistorey residential buildings;
- Educational institutions and youth education – kindergartens, schools, colleges, universities;
- Cultural institutions – palaces of culture, theater buildings;
- Administrative buildings of cities and towns;

Figure 3. Novotoshkivske village (population 2,119 people on January 1, 2022), Luhansk region [11].

- Complexes of public utilities and engineering structures to ensure the functioning of cities;
- Structures and complexes of public transport enterprises;
- Transport facilities – railway stations, airports;
- Industrial companies;
- Objects and structures of engineering networks for gas and electricity supply, drainage and sewerage, water and heat supply;
- Elements of road infrastructure;
- Parks, squares, recreation areas, landscape areas.

The above classification makes it possible to group objects according to the characteristics of the size of the territories and according to the principle of the priority of fixing the land plot (priority of the territory).

An individual residential building can be relatively easily assessed in terms of the nature of defects or the degree of destruction, the possibility of repair, and the cost of repair. But if this building is located on a plot of manor development, in which engineering communications are destroyed? The cost and laboriousness of laying or repairing engineering networks of electricity, gas supply, water supply can be several times higher than the cost of restoring a house. That is, the problem of a separate house should be considered within the framework of the task of restoring a certain area of the manor development. The second part of the problem is legal in nature – what to do if the owner or legal representative of the owner of the house is absent? How to resolve issues with the house and land? What parameters or factors are more decisive – the attractiveness of the territory or the degree of preservation of houses? Similar questions arise for apartment buildings, despite the fact that there will be even more uncertain positions for objects of this class.

The classical theory of town planning development is based on the evolutionary, gradual nature of transformations with the aim of improving the town planning situation [13, 14]. In our case, unfortunately, we have changes that are sudden, external in nature, partially catastrophic, partially leading to changes in the urban or regional situation radically [5]. Figures 4 and 5 show only a small part of the destroyed city of Popasna (the history of Popasna as a settlement begins in the middle of the 19th century). The city's economy was mainly focused on railway transport and the coal industry. A railway-car repair works, a locomotive bay and wagon depot, and an elevator operated in the city. The population of the city was up to 20,000 people.

Figure 4. Satellite image of the damaged locomotive bay and wagon depot in the city of Popasna, Luhansk region [15].

A recursion is fixed when the usage form changes as a result of a war. The impact of the war determines the changes in the function of the use of the territory. Change of function — if it is irreversible, determines the change in form during the period of post-war reconstruction. For example, to what extent the coal-mining part of the economy of individual cities will remain. Lisichansk is known to be the birthplace of coal-mining Donbass. Will it be economically feasible to keep the coal mines of Lisichansk?

If we draw an analogy with the Chernobyl disaster, there has also been a catastrophic change in the regional situation. For obvious reasons, part of the territory was withdrawn from usage, the residence and attendance of people in the Chernobyl Exclusion Zone was limited. However, this zone is under control, a number of programs have been developed aimed at stabilizing the general situation, special activities, construction, various types of research and control are

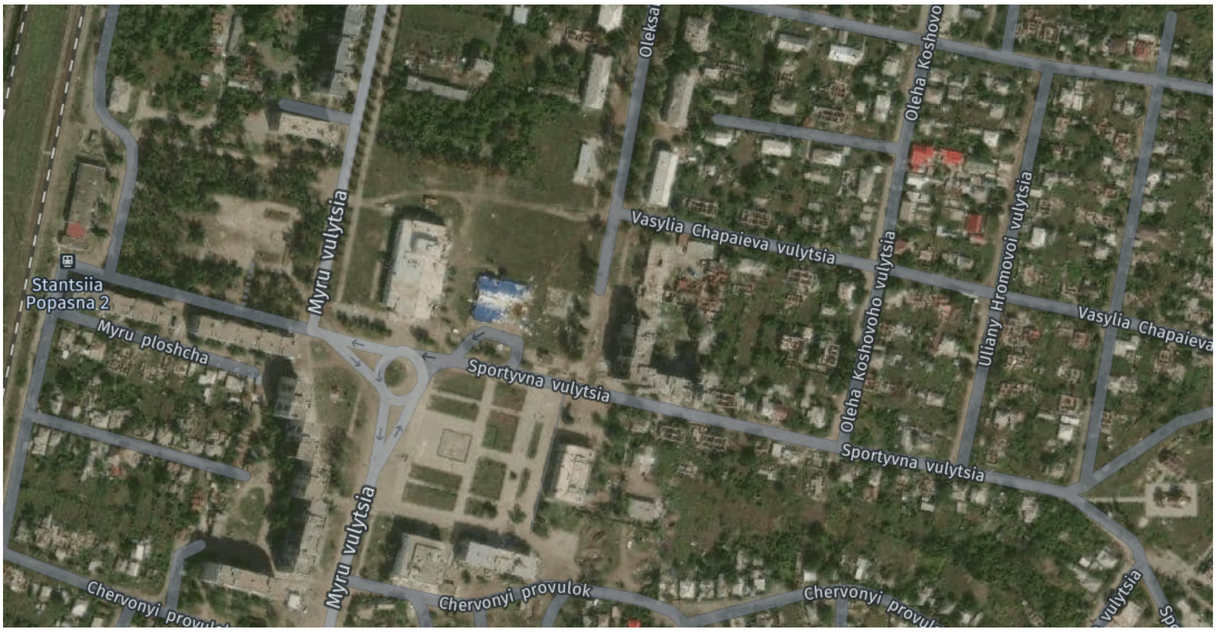

Figure 5. Satellite image of a part of the destroyed district of the city of Popasna, Luhansk region [15].

being carried out. But this exclusion zone is unprofitable, it generates losses. There is a balance between minimizing the harmful effects and the cost of maintaining the zone. After the liberation of the occupied territories, they must be returned to normal economic activity, profitable and generally useful. In this case, the problem arises of determining the balance between the costs of restoring territories destroyed as a result of hostilities and their further efficiency of use.

The situation in the temporarily occupied territories remains difficult, so far it is impossible to talk about fixing the general state of damage losses. Natural and climatic factors are a significant factor in changes and the winter period will make its own adjustments. In the context of the liberation of the territories, spring will give a rough idea of the scale and inevitability of the destruction of the housing stock. Damaged roofs of buildings and lack of heating will lead to soaking of the walls. Freeze and frost retreat cycles can reduce the bearing capacity of structures. Two seasons in a row will make the buildings uninhabitable.

Spring will give an idea of the influence of such factors as the level of urbanization, the scale of destruction (in percent), the availability of labor resources and the active share of the population on the preservation and development of the territory of the so-called Rubizhne-Sievierodonetsk-Lysichansk triangle.

A separate scientific task is to assess the impact of migration processes on the directions of the functional development of the territory [16]. Migration had a multi-vector character. Most of the citizens moved to Ukraine. Some of them turned out to be refugees in European countries. Some part went to Russia. Part of the population remained. Among them – most of the economically inactive population – pensioners. The percentage of the active part of the population has decreased – but now it is difficult to estimate its number, despite the fact that migration processes continue. Employable people are looking for an opportunity to leave for regions with higher salaries. This trend has been fixed in the Donbass for a long time [4, 17–19]. The war gave the character of a catastrophe. Since there are no socio-economic prerequisites for mass incentives for the return of able-bodied people, this trend is becoming irreversible. It can be argued that the period of intensive colonial development of Donbass has expired. The region cannot offer attractive working conditions and becomes a donor of labor resources. As already noted in previous studies [20], the region stagnates, the nature and directions of development of the territory are determined by the functional processes taking place on it. Apparently, it should be noted that the trends have not been finally determined, but the general direction is currently negative.

The cities of Luhansk region can be classified as industrial cities without a notable historical heritage. These cities have different planning structures and their own unique compositional construction. The consequences of destruction lead to the fact that the basic urban planning principles require adjustment. Changing the functions and form of territories is the task of restoration. At the initial stage, it is difficult to determine the dominant part. [21] Comprehensive reconstruction of destroyed cities is based on the principles of protection and safety; accessibility; autonomy; adaptability; attractiveness; environmental friendliness and restoration of the environment.

- *Principle of protection and safety.* The urban form should protect residents from various types of danger. For border regions, there is an existential threat of a resumption of war, and this factor must be taken into account.
- *Principle of accessibility.* For border regions, accessibility should be a basic direction towards the so-called center. The traditional concept includes both limitations and a combination with the principle of safety, including the ability to move quickly.
- *Principle of autonomy.* Creating resilient management systems. A sufficient level of infrastructure and resource provision is necessary for functioning and sustainable development.
- *Principle of adaptability.* The spatial and architectural-planning organization of the city should have a complex structure but be adaptable, flexible, and able to quickly respond to possible changes, corrections, and new trends.
- *Principle of flexibility.* The urban development management system should be more flexible. Feedback on problems and response time should be accelerated.
- *Principle of attractiveness.* The set of factors and conditions that will contribute to the return and attraction of people, enterprises, and capital.
- *Principle of ecological sustainability.* The restoration of the environment should be an active process.

The process of restoring liberated cities will have its atypical differences. Obviously, the beginning of everything will be the restoration of the management system in conditions of a state of emergency. Not all norms of civilian legislation will work. The primary actions will concern individual objects critical for the functioning of the liberated cities. The restoration process will be divided into three stages (directions) – object reconstruction, functional reconstruction, and urban (territorial) reconstruction. It will be difficult to determine the predominant direction at the initial stage. Different methods and types of work are developed for each stage. Work can be performed simultaneously or sequentially depending on the condition and characteristics of each group of buildings that form the restoration area, as well as the goals and financing of the reconstruction.

Based on a comparative study of buildings and structures within a residential block and determining new requirements for them, the tasks of reconstruction and measures of reconstructive intervention are identified [21]. The measures of reconstructive intervention depend on the level of suitability of individual buildings for normal operation; the degree of preservation of planning and volumetric spatial qualities of the site (scale of destruction); architectural-planning and structural qualities of individual buildings; the ability of buildings to meet urgent social needs, that is, whether they need to be given a new function.

Object reconstruction of buildings aims to restore their functional properties and primary housing qualities. The principles of object reconstruction include:

- Preservation of the primary architectural and planning solution of the building in the existing development (reconstruction involves partial restorative repair, capital repair, or modern conversion);
- Dominance of the overall reconstruction concept of the quarter in selecting project solutions for restoring the building.

Functional reconstruction of buildings and structures within a block aims to find the optimal modern functional use, taking into account the real condition of the block. Determining the optimal functional solution for a civil building is based on comparing the primary function of the building, its current state, and the possibility of transforming it to meet modern needs. The project solution may involve restoring the primary function, developing the primary function, or forming a new function for the object. Restoring the primary function is achieved through repairing and reconstructing the building using various methods. Alternatively, complete reconstruction of a ruined building is possible. Developing the primary function is achieved through reconstruction of the building using full reconstruction or partial modernization methods. Forming a new function (adaptation) is recommended during reconstruction of the building using partial or full modernization methods, primarily as part of a detailed planning project for a group of buildings. When choosing new functions for a historical building, it is essential to adhere to principles such as maximum similarity between the new and existing functions, and preserving the correspondence or proximity of the selected function to the previous purpose of the object.

The main principle of functional reconstruction of blocks with a complete or partial list of service objects may be the preservation and orientation towards multifunctionality. Choosing the correct functions for the block and its individual buildings, in combination with optimal means of reconstruction, may be the only way to ensure survival and development of the entire planning element as a whole.

Urban/territorial reconstruction includes the reconstruction of the spatial territorial structure as the basis for preserving and developing the main functions of the city. The reconstruction of the spatial structure aims to organize and adapt it to post-war realities. The principles of urban reconstruction include:

- maximum preservation of the existing spatial structure, which requires minimum investment in territorial transformation;
- addition and expansion of the spatial structure with new elements, taking into account the current state and post-war realities.

At this stage, the hierarchy of compositional structural elements of the level-agglomeration-urban planning unit is determined. Prospective territorial hubs are formed that provide for the development of the main functions of the city, and areas for deferred reproduction are reserved.

The research [22–24] identifies three models (forms) of reconstructive activity:

- The “restorative” reconstruction model;
- The “supportive” or “accompanying” reconstruction model;
- The “proactive” or “anticipatory” reconstruction model.

The proactive reconstruction model has a high level of stimulation for future activity, is designed for implementation over a period of 5-7 years, and results in a reconstruction concept or target program. The supportive reconstruction model has a medium level of stimulation for future activity, is designed for implementation within 5 years, and provides for the development of a reconstruction project (program). The restorative reconstruction model has a low level of stimulation activity, operates within a timeframe of 0.5-1 year, and involves the development and implementation of a reconstruction project for an object [22]. At the initial stage, situational response will be implemented for emergency restoration of urban objects and functions. This will be followed by a period of implementation of programs and projects for supportive and proactive reconstruction. Within 2-3 years, an adequate target program for the reconstructive development of urbanized territories should be developed. Object-oriented response and current development should be subordinate to the programmatic goals of the proactive reconstruction model. The figure 6 contains a scheme of methodical interaction of models of reconstructive activity. Situational response, which leads to systemic error, promotes the accumulation of problems and contradictions, ultimately resulting in the degradation of territories and regional crisis state, is a negative alternative.

There is a task to correctly assess and determine trends, which will allow determining the direction of changes. The situational analysis will allow to determine the tasks transformed in order to ensure the sustainable development of the region in the new conditions created by the post-war situation. After the occupation, it is necessary to develop a program of regional restoration/renewal covering the territory of the regions, town-planning formations (cities and settlements), infrastructure objects, objects and infrastructure systems of urban and group settlements. [25–28]

It is not possible to develop a separate city with leading indicators on the destroyed territory. The concentration of finances in a separate city (populated area) will not have a great effect in terms of improving the quality of life in the region. Likewise, spreading a thin layer of funding over the territory will not ensure its sustainable development. It is necessary to determine growth points, directions of advanced development and support a function that can provide a high level of benefit.

Orientation tasks and prerequisites that must be analyzed and solved at the first stage are quite numerous.

Administrative and territorial reform of the region (for example, what city will be the regional center or fulfill most of its functions) [29].

Will individual cities retain their status? For example, Hirske, Popasna, individual villages – completely destroyed, Rubizhne-Sievierodonetsk-Lysychansk agglomeration – perhaps more expedient as a single administrative entity? On the formation of military-civilian administrations of districts – former cities forming an agglomeration? Problems of the functioning of city councils and city executive committees of cities. Problems important for the normal functioning of cities have not been resolved for years: the political situation on the ground is far from normal, which means that important decisions should not be made at the level of local government.

Define zones that will have special border region conditions. As noted, the region from the internal, transboundary has become a border region [5, 20]. The state, the Ministry of Defense, the Armed Forces of Ukraine are likely to have priorities in the use of parts of the territory.

It is also necessary to determine the configuration – the supporting frame of communication routes, taking into account new realities. If there is a special regime zone, are the roads needed (P07 Chertkovo, T1 302 Tanyushevka, P22 Chervona Talivka, M04 Izvarine, E20 Dolzhansky)? Subject to the strict requirements of the visa regime, foreign citizens will have to travel on other routes. Certainly, undergo changes in the category of roads that have the direction of the road along the border, and unite the major cities of the regions.

This will determine (possibly) additional engineering structures, tasks for the restoration and reconstruction of existing bridges, flyovers, airfields, etc.

As an example, the Siverskyi Donets River on the border with Russia flows along the border line for a considerable distance – from the settlement of Novokievka/Makarov yar to the settlement Popovka. The river should be provided with means of control, protective structures.

It is possible that it will be necessary to regulate the flow of the Siverskyi Donets and create

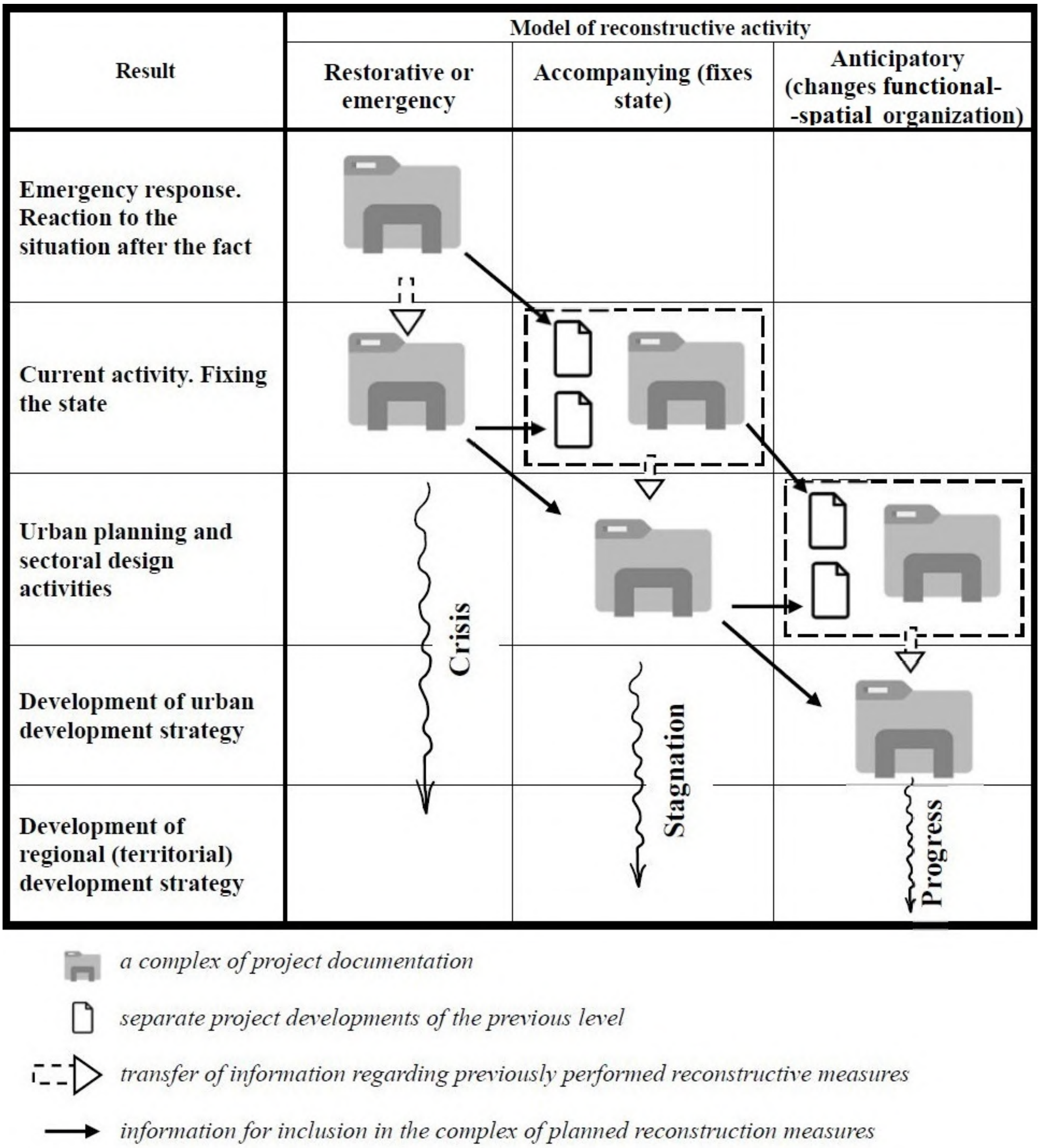

Figure 6. Scheme of methodical interaction of models of reconstructive activity.

additional water management complexes.

There is a need for a cadastre of enterprises and institutions that will operate in the region and be subordinate to the central executive authorities (correctional colonies, detention centers, military camps, training grounds).

Perhaps there will be zones and territories with limited use, which will need to be determined, for example — mined.

Determine the objects that should be financed by the state and include them in programs and general layouts for urban development.

It is necessary to determine the objects in which there is a need to ensure the sustainable development of cities and the region — schools, kindergartens, sports facilities, hospitals, clinics, homes for the elderly, administrative buildings. For example, in the city of Lysychansk, almost all administrative buildings were destroyed. And if the functions are listed, then the basic list contains the buildings of the city hall, the national police, the prosecutor's office, the court, the security service, the ambulance station, and the fire station.

Depending on the results of the administrative-territorial reform, it is expedient to determine the placement of universities, colleges, and student residence buildings. In the territories occupied since 2014, a large number of educational institutions remain, the property of which consists of buildings, structures, and land plots. Part of the displaced institutions of higher education were reorganized by merger. The Ministry of Education of Ukraine acts as the manager of the property. The owner is the State Property Fund of Ukraine. Leaving the region without education means leaving the region of the future. Thus, the location of the leading educational institutions in the region should be determined.

It is necessary to determine objects of a commercial nature, their legal status, conditions for further functioning. In the region, there are several large enterprises that require balanced legal decisions – coal mines, private and state, Lysychansk oil refinery plant, 'Zarya' chemical plant, Rubizhne cardboard mill, Sievierodonetsk chemical plant 'Azot' and others. One should hardly care about the development of the network of gas stations. Large networks of this segment will solve this problem at the level of commercial attractiveness. It is quite obvious that the network management wants to know the plans for the development of the road network in order to coordinate their projects.

4. Conclusions

The cities of Luhansk region are predominantly known for their industrial character and lack a significant historical heritage. The destruction caused by past conflicts has necessitated adjustments to the fundamental urban planning principles. The process of restoring these cities involves determining the dominant aspects and implementing comprehensive reconstruction based on the principles of protection, safety, accessibility, autonomy, adaptability, attractiveness, and environmental friendliness.

Given the military and special nature of certain territories, prioritizing their planning framework is essential. Cross-border cooperation has shifted towards establishing clear borders and protective exclusion zones. The delimitation and demarcation of borders have been gradual, and stricter border control measures are now in place.

The restoration of liberated territories requires a thorough review and update of general layouts and regional development schemes to focus on advanced programs and projects that facilitate the structural growth of the regions. The model of anticipatory reconstructive activity takes precedence in this regard.

To support the development of cities, it is crucial to establish and strengthen departments responsible for urban development tasks, such as the Chief Architect's office, with an expanded staff of specialists.

We propose the establishment of a Regional Civil-Military Administration department dedicated to urban and territorial development, staffed with qualified experts.

Urbanized areas with normal population density tend to be more successful and competitive in their development.

Investing in education and job creation should be prioritized over general improvements to the territory. This focus will play a crucial role in the region's growth.

Considering the anticipated population migration, the region is likely to experience a shortage of labor during recovery programs, particularly in the construction industry.

It is essential to allocate a portion of the territory for environmental purposes and landscape reproduction, such as preserving forests and riverine areas.

The preservation of ecologically significant areas should be a priority to maintain the region's environmental balance.

In summary, the restoration of the cities in the Luhansk region demands a careful reevaluation of urban planning principles, cross-border cooperation, and investments in education and job opportunities. Prioritizing environmental preservation and sustainable development will contribute to the region's long-term success and growth.

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References

[1] National Security and Defense Council of Ukraine 2021 Hlosariy nazv, terminiv ta slovospoluchennya, yaki rekomendovano vykorystovuvaty u zv'yazku z tymchasovoyu okupatsiyeyu Rosiys'koyi Federatsiyi Avtonomnoyi Respubliky Krym, m. Sevastopol' i okremykh rayoniv Donets'koyi ta Luhans'koyi oblastey URL https://www.rnbo.gov.ua/files/2021/%D0%93%D0%9B%D0%9E%D0%A1%D0%90%D0%A0%D0%86%D0%99.pdf
[2] Verkhovna Rada of Ukraine 2018 Zakon Ukrayiny Pro osoblyvosti derzhavnoyi polityky iz zabezpechennyam derzhavnoho suverenitetu Ukrayiny na tymchasovo okupovanykh terytoriyakh u Donets'kiy ta Luhans'kiy oblasti" URL https://zakon.rada.gov.ua/laws/show/2268-19#Text
[3] Tsentr Razumkova 2019 Viyna na Donbasi: realiyi i perspektyvy rehulyuvannya URL https://razumkov.org.ua/uploads/article/2019_Donbas.pdf
[4] Centre for Economic Strategy 2021 Diahnostychnyy zvit. Analiz problem ekonomichnoho rozvytku Donets'koyi ta Luhans'koyi oblasti. Ekonomichna transformatsiya Donbasu / Pidtrymka stratehiyi ekonomichnoyi transformatsiyi Donbasu URL https://ces.org.ua/wp-content/uploads/2021/04/UA2002-Diagnostic-report-on-the-current-state-of-Donbas-February-2021.pdf
[5] Sokolenko K V, Sokolenko V M, Filatiev M V and Chernih O A 2022 *IOP Conference Series: Earth and Environmental Science* **1049** 012079 URL https://doi.org/10.1088/1755-1315/1049/1/012079
[6] Krychkovskyi O 2022 V Zelens'kogo rozpovily, skil'ky mist okupanty povnistju znyshhyly v Ukraini URL https://tinyurl.com/m4nmdz4p
[7] Kovalenko M 2022 U Sivers'kodonec'ku rosijany znyshhyly 70% budynkiv, a Popasnu vidnovljuvaty ne zbyrajut'sja URL https://dyvys.info/2022/08/10/u-siverskodonetsku-rosiyany-znyshhyly-70-budynkiv-a-popasny-vidnovlyvatu-ne-zburaytsa/
[8] Rishard B 2001 *Ekonomichnyj chasopys* **9** 25–29
[9] 2023 V "LNR" prinjali novoe territorial'noe ustrojstvo. Razrushennaja Popasnaja bol'she ne schitaetsja naselennym punktom URL https://tinyurl.com/4unysc3d
[10] 2022 Okkupanty nastupajut na Severodoneck, imejut chastichnyj uspeh – Luganskaja OVA URL https://tinyurl.com/2p86kmdp
[11] Klimkovetckii M 2022 rossijskie okkupanty "srovnjali s zemlej", a zatem zahvatili Novotoshkovskoe v Luganskoj oblasti — glava OVA URL https://tinyurl.com/5a76h3rw
[12] Cabinet of Ministers of Ukraine 2003 Nacional'nyj standart N 1 "Zagal'ni zasady ocinky majna i majnovyh prav" URL https://zakon.rada.gov.ua/laws/show/1440-2003-%D0%BF#Text
[13] Osytnyanko A 2001 *Planuvannya rozvytku mista* (Kyiv: KNUBA)
[14] Demin N M 2012 *Mistobuduvannya ta terytorial'ne planuvannya* **45**(1) 3–15 URL http://library.knuba.edu.ua/books/zbirniki/02/2012451.pdf
[15] 2023 HERE WeGo URL https://wego.here.com/?map=48.64455,38.36635,16,satellite
[16] Apostolova L O, Mamedov A M and Osytnyanko A P 1999 *Mistobuduvannya ta terytorial'ne planuvannya* **4** 11–34
[17] The Luhansk Region Military Civil Administration 2020 Prohrama ekonomichnoho ta sotsial'noho rozvytku luhans'koyi oblasti na 2021 – 2023 roky URL http://loga.gov.ua/sites/default/files/collections/201228936.pdf

[18] 2015 Svitovyy bank, Mizhnarodnyy bank rekonstruktsiyi ta rozvytku: Ukrayina. Ohlyad urbanizatsiyi, Zvit Svitovoho banku №: ACS15060 Tech. rep. The World Bank Washington, DC URL `https://documents1.worldbank.org/curated/en/787061473856627628/pdf/ACS15060-REVISED-PUBLIC-UKRANIAN-ukr-web-text-cover.pdf`
[19] Dolishniy M I (ed) 2001 *Regional'na polityka: metodologija, metody, praktyka* (Lviv, Ukraine: Dolishniy Institute of Regional Research of NAS of Ukraine)
[20] Sokolenko K, Chernykh O and Sokolenko V 2021 *Mistobuduvannya ta terytorial'ne planuvannya* **77** 428–440 URL `https://doi.org/10.32347/2076-815x.2021.77.428-440`
[21] Leshhenko N A 2021 *Suchasni problemy arhitektury ta mistobuduvannja* **59** 203–214
[22] Pleshkanovs'ka A M 2013 *Metodologija kompleksnoi' rekonstrukcii' mista* Dissertation for obtaining the scientific degree of Doctor of Technical Sciences Kyiv National University of Construction and Architecture
[23] Pleshkanovs'ka A M 2005 *Mistobuduvannja ta terytorial'ne planuvannja* **21** 275–280
[24] Pleshkanovs'ka A M 2013 *Suchasni problemy arhitektury ta mistobuduvannja* **34** 377–384
[25] Bilokon Y N 2003 *Rehyonal'noe planyrovanye (teoryya y praktyka)* (Kyiv: Lohos)
[26] Bilokon Y N 2002 *Funkcija ta struktura formy v regional'nomu planuvanni* (Kyiv: Kyj)
[27] Bilokon Y N, Vladymyrov V V and Fomyn Y A 2002 *Organizacija territorii prigranichnyh rajonov (konceptual'nye polozhenija)* (Kyiv: KNUBA)
[28] Artyomov I, Varnaliy Z, Goblyk V, Dinis G, Dius N, Yevtukh M, Kampov L, Kish E, Kovach V, Lendiel M, Lugovyi V, Oleksyk H, Ofitsinsky R, Polyuzhyn M, Prikhodko V, Pugachevska K, Yasetska-Ustych S, Rovt O, Roman S, Rudenko O, Talanova J, Terentieva N and Ustych S 2012 *Cross-border cooperation of Ukraine: state, problems and prospects* (Uzhhorod: Grazhda) URL `https://www.uzhnu.edu.ua/en/infocentre/get/6059`
[29] Ostapenko P, Perkhalyuk R, Bonchkovs'kyy O and Ostapenko S 2021 *Atlas administratyvno-terytorial'noho ustroyu Ukrayiny* 2nd ed (Kyiv) URL `http://web.archive.org/web/20220217061125/https://atu.decentralization.gov.ua/`

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Transformational processes of ensuring sustainable urban development: the realities of Ukraine

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Transformational processes of ensuring sustainable urban development: the realities of Ukraine

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Abstract. The purpose of the study is to determine the state of transformational conversions in Ukraine on the way to achieving the goals of sustainable development, in particular, the condition of the development of cities and communities. With this goal, an analysis of Ukraine's position according to indicators of sustainable development in dynamics was carried out. It has been established that Ukraine is committed to the values and goals of sustainable development. An assessment of measures regarding the adaptation of sustainable development goals in Ukraine was conducted. It has been found out, that Ukraine has made progress in achieving twelve of the 17 goals that determine the country's sustainable development in the economic, social, and environmental spheres, including SDG 11 "Sustainable cities and communities". The state and amounts of financing of the "Stable cities and communities" goal were analyzed, and the disadvantages of the Ukrainian system of state strategic planning and budgeting were identified. Proposals regarding the innovative nature of economic development in the context of sustainable development of cities and communities have been researched and substantiated. Approaches to the management and development of cities and communities are proposed, which should be based on inclusiveness, safety, and sustainability principles.

1. Introduction

In the modern activity of mankind, issues related to various aspects of cities sustainable development are considered key factors in the development of the modern economy. The sustainable development of spatial systems, as a form of organization and ensuring a high quality of human life, gave impetus to changing approaches and strategies in the development of states, regions, cities, and territorial communities. The principles proposed by the international and European community, outlined in the Leipzig Charter "European Cities on the Path to Sustainable Development", the Strategy for Smart, Sustainable and Inclusive Growth "Europe 2020" and the UN Global Sustainable Development Goals are an illustration of approaches to sustainable development at the micro-, meso-, macro- and mega-levels. The conceptual principles of managing the sustainable development of the city are based on the guiding principles and regulations of the European Union, namely: the Charter of the Congress of Local and Regional Authorities of Europe (Strasbourg, 1957), the European Charter of Regional Spatial Planning (Torremolin Charter, 1983), the European Charter of local self-government (Strasbourg, 1985), the Gothenburg Strategy for the Sustainable Development of Europe (Gothenburg, 2001), the Leipzig Charter for the Sustainable Development of the City (Leipzig, 2007), the Europe 2020 Strategy "A strategy for smart, sustainable and inclusive growth" (Brussels, 2010).

The sustainable development of cities makes them viable, able to adapt, mitigate adverse consequences, and stimulate positive socio-economic and environmental changes. Sustainable development covers all aspects of the healthy development of the city and should provide solutions to financial, economic, social, and environmental problems.

2. Research methods

The research methodology is based on a literature review, survey, and qualitative case study.The authors analyzed scientific publications from the scientometric database for the period 2014-2020 regarding the reflection in them of aspects of sustainable development of territorial communities and cities. This made it possible to identify specific features of development in Ukraine. For an in-depth analysis, the authors used a case study. The work uses methods of generalization and comparison to determine the level of sustainable development goals in Ukraine and other countries of the world.

The purpose of the study is to determine the state of SDG 11 in the realities of Ukraine and compare it with other sustainable development goals and determine the place of Ukraine in indicators of sustainable development.

3. Research results

At the end of the 20th century, the principles of sustainable development were approved by the world community at the UN Conference on Environment and Development in Rio de Janeiro (1992) and finalized in the UN report "On Human Development" in 1994 into a universal concept of sustainable development. The essence of the concept of sustainable development in its modern understanding is the balance of social development in social, ecological, and economic aspects. Sustainable development is the development that satisfies all spheres of society's life without harming the opportunities of future generations [1]. Historically, Ukraine's path to sustainable development began at the same conference in Rio de Janeiro, when the Rio de Janeiro Declaration and Agenda for the Program of Action in the 21st Century were signed. Subsequently, Ukraine confirmed its desire to follow this path and, as a result, in 1997, the National Commission for Sustainable Development was created under the Cabinet of Ministers of Ukraine.

In 2015, in New York, as part of the agenda of the summit "Transforming our world: an agenda in the field of sustainable development until 2030", the UN General Assembly approved 17 sustainable development goals aimed at fighting poverty, protecting the planet and improving the lives and prospects of everyone, around the world and called on countries, the public sector and business to unite for their implementation. Goal number 11 is the sustainable development of cities and communities [2].

Since 2015, several reforms have been launched in Ukraine (figure 1) aimed at implementing socioeconomic transformations and strengthening the democratic system. The Sustainable Development Goals (SDG) are integrated into a public policy based on "leaving no one behind". The result of the inclusive SDG adaptation process for Ukraine, taking into account the specifics of national development, was the SDG system, which consists of 86 tasks with 183 indicators for monitoring. The government established an Interdepartmental Working Group on SDG issues to coordinate work on achieving the goals. For now, the responsibility of the ministries for SDG tasks has been established, the President of Ukraine has adopted a Decree that attaches the Goals as a reference point for the development of program and forecast documents, and an SDG monitoring system has been developed. In 2019, an analysis of the degree of SDG incorporation (at the level of SDG tasks) was carried out. In total, 17 goals and 86 national tasks of the SDG are incorporated into 162 regulatory and legal acts of the Government, 1,394 goals, and 4,296 measures established in these acts are aimed at the implementation of goals and tasks. But, despite a significant number of state strategic documents and a large volume of tasks and measures, not all tasks of the 17 goals are taken into account [3–5].

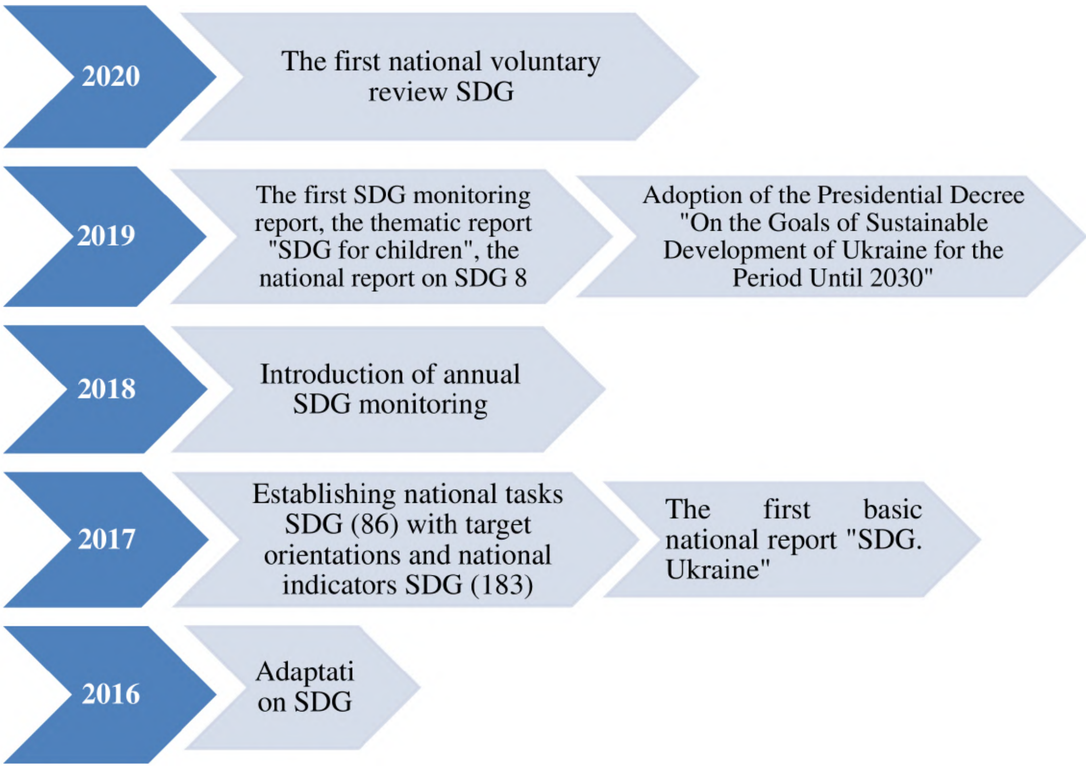

Figure 1. Statistics of actions related to the adaptation of sustainable development goals in Ukraine (based on [3–5]).

In 2021, according to the Sustainable Development Goals Index (SDG 2022) (figure 2), Ukraine took 37th place out of 163 countries, ahead of Australia (38th place), Lithuania (39th) and the USA (41st). Finland, Denmark and Sweden occupy the first places in the ranking of the SDG 2022 index, and the Central African Republic and South Sudan are the last [6].

Studies show that in 2021, progress is being made in Ukraine in achieving twelve of the 17 goals that determine the sustainable development of the country in the economic, social, and environmental spheres, including SDG 11 “Sustainable cities and communities” (figure 3). Ukraine has made the most progress in achieving the goal of “universal elimination of poverty in all its forms”. At the same time, Ukraine did not deteriorate its position in any of the basic objectives. However, the analysis of state strategic documents points to the disadvantages of the Ukrainian system of state strategic planning and budgeting. Thus, a large number of strategic and programmatic documents for 17 targeted areas of development leads to unclear coordination of efforts to achieve goals and perform tasks, forms a discrete rather than a systematic approach to policy formation, scatters financial, material, and human resources prevent the ability to concentrate on the efficient use of resources to achieve a certain result. The consequence of the lack of systematic work is, among other things, underfunding of important tasks and measures, low degree of their implementation, duplication of functions, tasks, and measures between executive authorities, and low responsibility for failure in the achievement of results.

In general, in the world ranking of indicators of sustainable development, Ukraine occupies not the worst, but also not the best positions. Thus, in 2020, according to the international analytical organization Legatum Institute, Ukraine took 92nd place in the ranking of the well-being of countries, which is 4 positions higher than in 2019 (figure 4). At the same time, among all the countries of Eastern Europe, Ukraine ranks last in the rating. The reason for this is

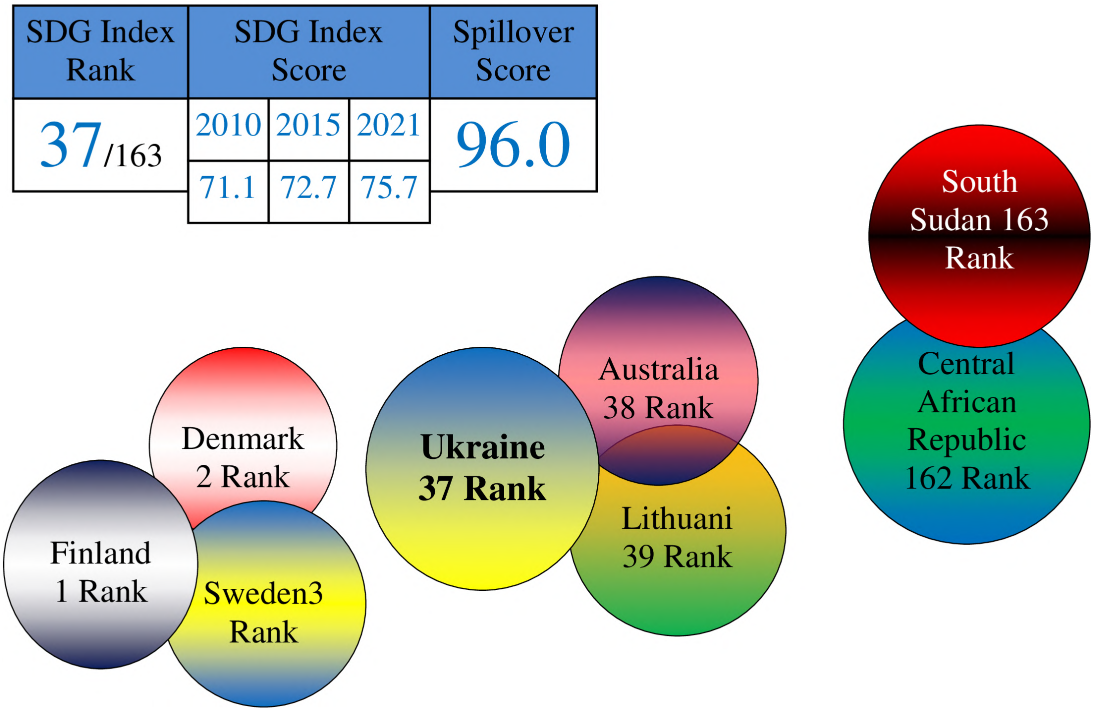

Figure 2. Ranking and score of Ukraine according to the SDG 2022 index (based on [6, 7]),

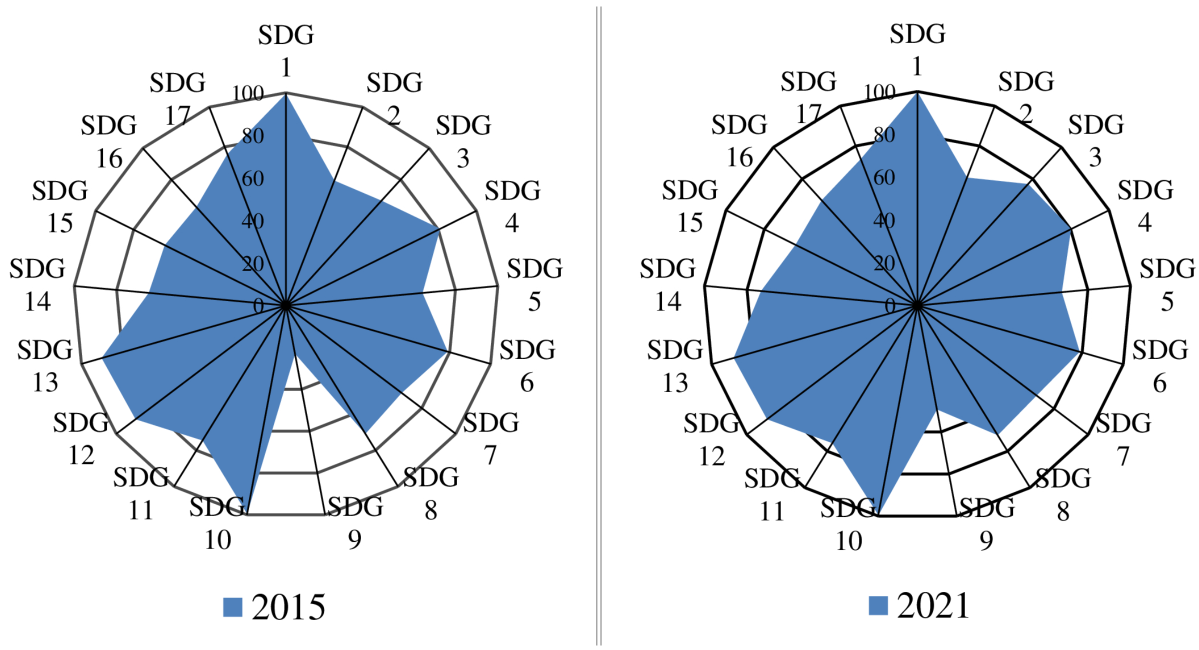

Figure 3. The average value of achieving the goals of sustainable development in Ukraine (based on [7]).

the war in the East of Ukraine, which has been going on since 2014, which significantly lowers Ukraine's security rating (to 144th place out of 167). In addition, there are problems in the sphere of freedom of assembly and association in Ukraine, and indicators of religious tolerance in Ukraine have increased in recent years. The first places in the Legatum Institute rating are occupied by Denmark, Norway, and Switzerland. The last two are the Central African Republic and South Sudan [8].

Ukraine belongs to the developing countries, and according to the results highlighted in the latest report on the Inclusive Development Index in 2018, it ranked 49th among 74 developing countries. Lithuania, Hungary, Azerbaijan, Latvia, and Poland are 5 developing countries that are leading in terms of inclusiveness of economic growth. Norway, Iceland, Luxembourg, Switzerland, and Denmark are among the top five countries developed by the level of inclusiveness of economic growth. Ukraine's development trends indicate that the inclusiveness of its economic development decreased by 6,8 percent from 2014-2018. In particular, the distribution of wealth in Ukraine is one of the most uneven among all developing countries. At the same time, the level of income inequality and the level of poverty in Ukraine is low: the middle class, in the opinion of WEF experts, remains numerous, health care and support for the unemployed are at a sufficient level, and the education system contributes well to inclusive growth. However, constant wars in the east of the country contribute to regression, as they disproportionately affect the poorest strata of the population, prompting talented people to leave the country in search of opportunities for self-realization. The priorities are to increase the level of professional education, reduce the administrative burden on the creation of new enterprises, expand the financing of entrepreneurs and increase attention to the fight against corruption [9–11].

According to the current Environmental Performance Index (EPI), in 2022 Ukraine ranked 52nd among 180 countries in the world, and Ukraine has advantages in rational nitrogen management [12]. For reference, in 2020 and 2018, Ukraine ranked 60th and 109th, accordingly [10], and in 2016, it ranked 44th in almost all indicators, including water quality and air cleanliness.

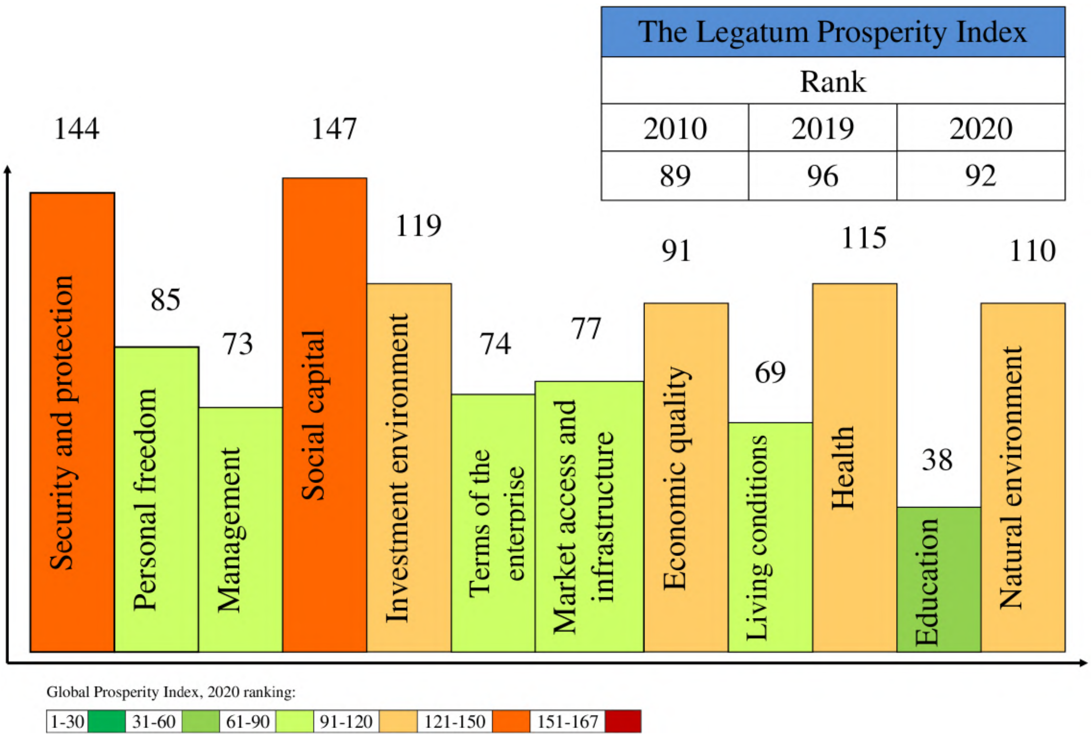

Figure 4. Ranking of Ukraine according to the Legatum Prosperity Index (based on [8]).

The current situation in the economy of Ukraine is characterized by not very high innovation activity, which is primarily related to the lack of own funds for enterprises and limited budget funding. Thus, according to the Global Innovation Index 2022 global innovation rating, Ukraine took 57th place out of 132 economies, holding the 4th position among 36 countries of the lower-middle income economic group, and is 34th among 39 European economies. Compared to previous years, Ukraine slightly worsened its results (for comparison, in 2021 – 49th, in 2020 – 45th, in 2019 – 47th, and 2018 – 43rd place, accordingly). Switzerland is recognized as the most innovative country, immediately after is USA, Sweden, Great Britain, and the Netherlands. It is also noted that China approached the TOP-10 innovative economies of the world (11th place), while Turkey and India entered the TOP-40 for the first time [13, 14].

As already mentioned above, of the seventeen sustainable development goals approved by the UN General Assembly in 2015 within the framework of the agenda of the summit "Transforming our world: agenda in the sphere of sustainable development until 2030", goal number 11 is the sustainable development of cities and communities.

The tasks of sustainable development of cities and communities include ensuring by 2030: access to sufficiently safe and inexpensive housing, safe, inexpensive, and environmentally sustainable transport systems, open for all and ecologically sustainable urbanization, preservation of world cultural and natural heritage, reduction of damage from natural disasters, reducing the negative environmental impact of cities, ensuring access to safe and open to all green zones and public places, improving the quality of national and regional development planning, implementing a comprehensive management approach in cities and settlements, assisting the least developed countries in the construction of sustainable and durable buildings.

Cities are the dominant form of socioeconomic organization and engines of the economic growth of any country. Among the variety of modern urban concepts, sustainable development has the longest history and the widest recognition in the world, but recently the Smart City concept has become increasingly popular. Smart sustainable cities become "innovative cities that use informational and communication technologies and other means to improve the quality of life, the efficiency of cities work and services, and competitiveness, while ensuring accordance of the needs of current and future generations in terms of economic, social, environmental, and also cultural aspects [15].

Rapid urbanization leads to ineffective allocation and application of resources, overtime increasing the burden on the environment. Enterprises that work in cities and contribute to overall economic prosperity have the opportunity to support infrastructure development by participating in the elaborateness of strategies for the development of cities and communities, using their capabilities and knowledge to identify innovative and economically effective solutions to complex, interdisciplinary issues of urban sustainability.

Realizing their responsibility, communities, and cities all over the world are increasingly paying attention to issues of sustainable development, and Ukraine is also trying to keep pace with global trends. As of January 1, 2022, Ukraine has accrued 461 cities (including 2 cities with special status). The urban population in Ukraine, as of January 1, 2022, is 28 million and 693 thousand people, which is 69.7 percent [16].

Studies show that, despite Ukraine's clear movement towards achieving the goals of sustainable development, funding for SDG 11, although high at the current stage, but still not sufficient from the side of Ukraine, as well as international institutions. The main source of funding for regional development is several subventions from the state and local budgets. One of the tasks of Goal 11 is to increase housing affordability: this goal is financed from local and state budgets. To the objectives of SDG 11, local authorities are developing regional development strategies, although some communities have not yet completed this task. Such programs are developed by the communities themselves and at the expense of international technical assistance (ITA) projects. The level of housing and communal services financing remains low. In addition, neither state nor local budgets allocate appropriate funds for financing ecologically sustainable development. Also, it can be noted that most of the projects implemented in the public sector aimed at the realization of SDG 11 do not find support from international financial institutions (IFI). In the structure of bank loans granted in 2021, which can be conditionally divided into sustainable development goals, only 8 percent was issued for the development of SDG 11.

The assessment of the financing of sustainable development goal 11 "Sustainable cities and communities" for the period 2017-2020 shows that these are investments by state-owned enterprises in construction, restaurants, and hotels. In particular, these are investments in state project institutions, housing and communal enterprises of central state authorities, etc. Private investment financing of SDG 11, which includes investment in urban development (primarily investment in operations with real estate, hotels, and restaurants and 50 percent of investment in construction), can be assessed as high, (figure 5).

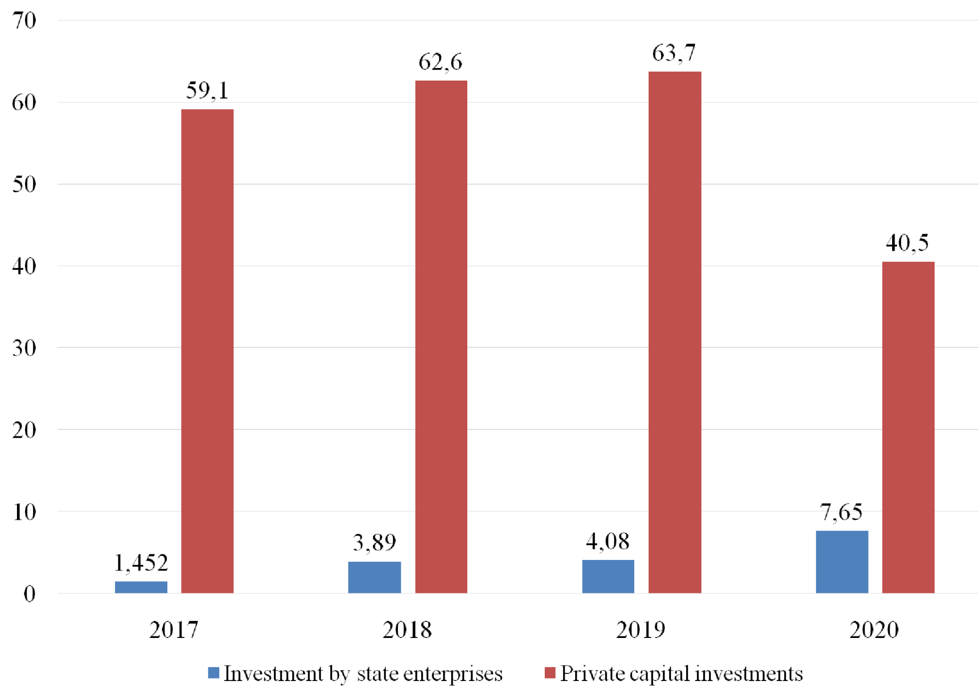

Figure 5. Financial investments in SDG 11 in Ukraine within the framework of the state and private sector, million UAH (based on [17]).

International technical assistance (ITA) is one of the important mechanisms for financing sustainable development in Ukraine. Ukraine, as a developing country, has been receiving ITA since 1992 and quite actively uses this financial instrument in almost all sectors of the economy. ITA projects also paid significant attention to SDG 11 "Sustainable Cities and Communities". 326 million dollars were allocated for SDG 11 to implement 119 projects in such sectors as "Regional development", "Culture and historical heritage", "Development of youth and sports", "Decentralization and promotion of regional development" and partially in the sector "Development of social infrastructure and services". In particular, these projects are aimed at supporting the natural reserve fund of Ukraine, helping local self-government bodies improve the management of resources and services by community priorities, increasing the role of cultural heritage sites as tourist destinations, improving the effectiveness of work with youth and the quality of youth policy at the local and national levels. The main projects in 2016-2020 within the framework of SDG 11 were the US projects "Decentralization that ensures better results and efficiency" (DOBRE), "Ukrainian national identity through youth" and the EU project "U-LEAD with Europe: Ukraine – expanding opportunities on places, accountability, and the Development Program".

The sustainable development of cities and communities in Ukraine is also ensured by special programs of the Ministry of Development of Communities and Territories, including SFRD. Community development budgets are also important. Priorities of regional development and tasks related to their implementation are determined by the State Strategy of Regional Development for the period until 2027. To fulfill this, appropriate regional strategies have been accepted. At the same time, some communities in Ukraine still have not developed and approved development strategies. The importance of the strategies lies in the fact that they allow enterprises to understand the local government's policy regarding the development of the relevant community and to estimate the amount of funding for the implementation of the planned changes.

Different proposals and approaches to local development strategies suggested by different projects complicate the implementation of strategic planning at the community level. One of the tasks of this goal is to ensure housing affordability. Several state programs are aimed at this. These programs are implemented by state institutions, whose source of statutory and operating capital formation is the state budget. Among them are programmed to reduce the cost of mortgages and housing rent for representatives of certain professions, which are implemented by the State Fund for the Assistance of Youth Housing Construction and the Entrepreneurship Development Fund (7 percent affordable mortgage).

However, today in Ukraine, as a result of the full-scale war, the situation in the direction of achieving the goals of sustainable development, in particular sustainability and cities, has significantly worsened, Mariupol, Volnovakha, Rubizhne, Popasna, Liman, and Severodonetsk were completely destroyed. The situation in the occupied communities of the Kherson region is very difficult. Some communities of the Mykolaiv region and Zaporizhzhia suffered significant destruction. In Kharkiv, part of the Northern Saltivka micro-district was also destroyed. Due to Russia's war against Ukraine, millions of citizens lost their homes. According to preliminary calculations by the Ministry of Community and Territorial Development, more than 2.4 million Ukrainians live in destroyed or significantly damaged dwellings. This is a preliminary figure because, in the conditions of martial law and temporary occupation of some regions, it is impossible to accurately calculate the number of uninhabitable housing. According to the data given by the regional military administrations, from February 24 to October 18, 2022, almost 160,000 damaged or destroyed objects were recorded in the territories available for counting. 60 percent of them have a degree of destruction of more than 50 percent. Among the damaged real estate objects, residential premises predominate – more than 142,000. Of them, more than 54,000 are with a degree of destruction up to 50 percent, and 88,000 are 50-100 percent [18].

As of June 2022, the cost of direct damage has reached more than 97 billion US dollars, and as of February 2023, losses are estimated at 135 billion US dollars. Most affected were residential buildings (40 percent of total damage in 2022 and 38 percent in 2023), transportation (31 and 26 percent, respectively), energy (3 and 8 percent, respectively), and trade and industry (10 and 8 percent, respectively). Donetsk, Kharkiv, Luhansk, Zaporizhzhya, Kyiv, and Kherson regions are the most affected (figure 6). Disruptions to economic flows and production, as well as additional war-related costs, are collectively estimated as losses of US dollars 252 billion as of June 2022 and US dollars 290 billion as of February 2023 [19, 20].

In the first quarter of 2022, Ukraine's gross domestic product (GDP) contracted by 15.1 percent year-on-year, and the poverty rate is expected to increase from 2 percent to 21 percent (based on a poverty line of US dollars 5.5 per person per day). The cost of the need for reconstruction and restoration, as of June 1, 2022, is estimated at more than 349 billion US dollars, which exceeds the GDP of Ukraine in 2021 by more than 1.6 times [19]. As of April 2023, according to the updated data of the damage assessment and recovery needs (RDNA2),

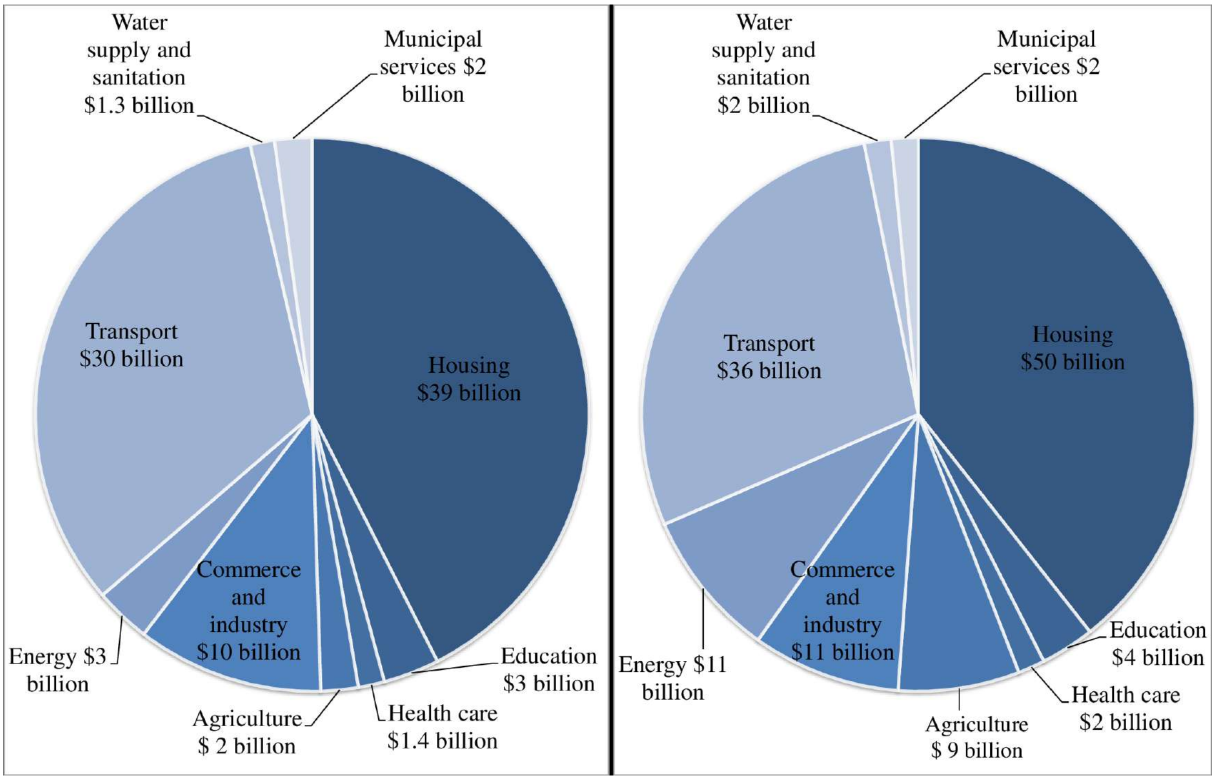

Figure 6. The total amount of damage caused to the cities and territories of Ukraine as a result of the full-scale war (based on [19, 20]).

the needs of our state for reconstruction have increased to 411 billion dollars (this is 2.6 times more than the projected GDP of the country in 2022) [21].

As shown in figure 7 according to the calculations made in 2022, extremely large losses and needs of financial resources are needed to restore the infrastructure of cities, in particular, the transport sector (21 percent), housing (20 percent), energy (3 percent), the sector of social protection and means of livelihood (6 percent), liquidation of explosive objects (9 percent), etc. [19]. However, the 2023 figures indicate that the level of destruction is steadily increasing and, according to the assessment, the greatest recovery needs are in the transport sector (22 percent), housing (17 percent), energy (11 percent), social protection, and livelihoods (10 percent). The greatest increase in the level of destruction is noted in the energy sector (increased more than fivefold compared to June 2022) [20, 21].

In 2022, Ukraine's GDP fell by 29.2 percent, 13.5 million people were displaced in Ukraine and Europe, millions lost their homes, and 7.1 million people were below the poverty line as poverty rose from 5.5 to 24.1 percent, setting the country back 15 years. In general, the achievement of many Sustainable Development Goals (SDGs) as a result of military actions is extremely difficult to sustain and achieve shortly, especially those related to poverty, health, education, energy, industry, peace, and justice, sustainable development of cities and communities. After the end of the war, all cities, including the infrastructure, will need to be rebuilt, but it must be rebuilt based on the principles of sustainable development. That is, it will be necessary to make important decisions and take important steps so that cities in the future become modern, innovative, inclusive, low-carbon, resistant to disasters and climate change, and meet the standards of the European Union. Despite the huge total amount of funding, the experience of other countries shows that reconstruction takes many years and a phased approach is critical.

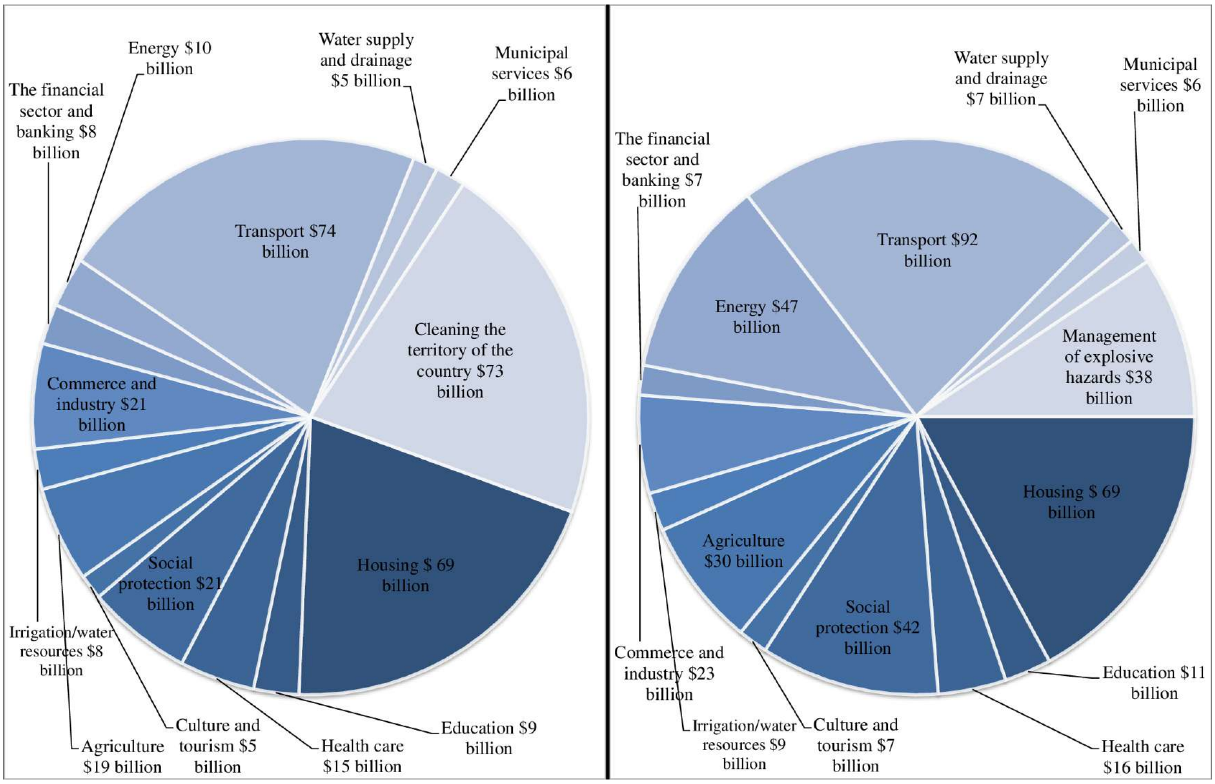

Figure 7. The total volume of needs for the reconstruction and restoration of cities and territories of Ukraine as a result of a full-scale war (based on [19–21]).

At the same time, it should be understood that the implementation of sustainable practices in cities and communities is not just a process that can be implemented in a month or a year. This requires additional investments, also the approval and realization of the State Regional Development Strategy, ensuring appropriate coordination of the process of implementation of regional development strategies in all regions based on smart specialization, strengthening the connection between strategic, spatial, and budget planning, reducing the negative impact of polluting substances on the environment, including the environment of cities, through the use of innovative technologies, etc., which will contribute to the transformation of large cities into rational and sustainable communities, the residents of which will be able to enjoy such advantages as reducing energy costs, improving the quality of services, reducing the amount of waste, creating a more favorable urban environment, creating opportunities for economic activity and development.

The recovery and reconstruction plan after hostilities in Ukraine should also be based on the following principles.

- *Inclusivity and equality.* Recovery and reconstruction must be closely linked to efforts to strengthen social inclusion and gender equality. That is, it is necessary to act according to the principle of "sustainable cities for people and created by people". Inclusivity starts with transparency and public participation. People must understand the consequences of local government decisions on community development and participate in their development.
- *Sustainability and reconstruction are based on the "build back better" principle.* The main part of Ukraine's infrastructure was built during the Soviet era and, at the same time, was constantly worn out due to insufficient funding. Today, the country's infrastructure

needs restoration in war-affected territories and radical modernization in territories where military operations did not take place. Rehabilitation and modernization must be carried out by climate change and sustainable development goals. For example, the road network suffers from a chronic lack of maintenance and repair, as well as needs major repairs, and more than half of the water supply networks are in critical condition. Social infrastructure is also not in the best condition, in particular schools, kindergartens and basic healthcare facilities are outdated and in need of reconstruction and modernization, as well as increased energy efficiency and increased resilience to climate change. Ukrainian industry and the energy sector will also need to adapt to best practices and standards that provide for higher efficiency and greater sustainability. For cities to be sustainable, urban infrastructure must be sustainable. According to the United Nations Environment Program (UNEP), sustainable infrastructure systems are "planned, designed, constructed, operated and decommissioned in such a way as to ensure the economic, financial, social, environmental (including resilience to climate change) and institutional sustainability of the entire infrastructure life cycle". This infrastructure can be nature-based, conventionally built, or combine elements of both to form a hybrid infrastructure. Building with nature, not against it, has direct benefits for cities. The term natural infrastructure (NBI) includes areas or systems that use nature to provide infrastructure services to people, the economy, and the environment. Examples of NBI include natural ecosystems such as forests, mangroves, wetlands, and grasslands. But NBI can also include engineered or "grey" structures that include natural solutions such as rain gardens and green roofs [22].

- *Local solutions and local development.* Restoration, revitalization, and modernization must be designed and implemented in such a way as to support the local economy. Any structure or process related to recovery and revitalization must utilize the economic and human capital of the country. Modernization of social infrastructure, housing stock, and transport infrastructure must be carried out based on the development and needs of the local community, business, and industry.
- *Focusing on community needs.* Community-based development, with the active involvement of citizens, is a key component in building a sense of ownership and ensuring the sustainability of recovery and revitalization. Innovative approaches are essential to ensure the participation of the entire local community in restoration and revitalization. Community needs cannot be identified through a top-down approach, and any such attempt can only lead to investments that are not linked to real needs on the ground and are unlikely to deliver sustainable results.

4. Conclusions

Based on the conducted research, it was established that since 2015, several reforms aimed at achieving the goals of sustainable development have been introduced and started in Ukraine, which is integrated into the state policy based on "leaving no one behind". However, despite the great number of efforts and the development of normative documents, not all tasks of the sustainable development goals are taken into account and fulfilled.

From year to year, progress is constantly observed in Ukraine in achieving the goals of sustainable development, including SDG 11 "Sustainable cities and communities". In the world ranking of indicators of sustainable development, Ukraine is not a leader, but it is not lagging either. Despite the efforts and significant work carried out by Ukraine in the direction of achieving the goals of sustainable development, the financing of SDG 11, although it is observed, and it can be said that its level is high, however, it is not sufficient from the side of Ukraine, as well as international institutions. Today and in the future, the model of inclusive growth in Ukraine should be based on the European experience and guided by the principles of intellectual, sustainable, and comprehensive development. If we turn to history, then Stefan Füle's remark at the meeting of the Ukraine-EU Parliamentary Cooperation Committee in Brussels on March 22-23, 2010, that Ukraine now needs "concrete reforms, not just encouraging words", is still relevant today.

What is necessary today is a better understanding of the importance of achieving the SDG both at the central and local levels, as well as improving the skills of civil servants and deputies at all levels, which requires the development and conduction of training on relevant topics, including the methodology of financial development assessment and operational comprehensive assessment, to the program of advanced training courses for civil servants. In particular, special programs on issues of sustainable development and achieving the SDG, analysis of poverty and social impact should be introduced. The SDG cannot be achieved without the active role of national business. The development of corporate social responsibility of business in such conditions is extremely important.

The post-war reconstruction of Ukraine and its further development should cover as much as possible the management organization of sustainable territorial development for the short, medium, and long-term perspective at the state, regional, and local levels. In the process of defining the SDG, relevant tasks, and indicators for a long-term perspective, it is necessary to take into account global development guidelines, principles of sustainable development, and public opinion regarding the vision of future development. World experience shows that social progress largely depends on maintaining a balance between the goals of supporting the economic growth of territories, business competitiveness, ensuring environmental safety, and reducing social inequality. Organizations, without exception, in their daily work have to take into account the goals and principles of the SDG, as external general settings, landmarks, and beacons that determine only the direction, what to strive for, and what to be for this.

Ensuring a sustainable future for Ukraine is possible through the development and implementation at the national level of the strategic and target foundations of state regulation of the country's sustainable development. Accordingly, the research on conceptual approaches to ensuring sustainable development in Ukraine, the definition of modern vectors of sustainable development of territorial communities in the conditions of post-war reconstruction acquires particular relevance.

Restoration of critical infrastructure, ensuring the energy security of the country (SDG 7, 9, 11). The planning of the restoration of the territories of Ukraine must be effective, in terms of the restoration of the life activities of cities, rural territories, and their communities, the authorities are endowed with the appropriate powers. Government representatives must make high-quality, effective, long-term systemic decisions. The best international experience of rebuilding cities after large-scale destruction shows that only an integrated approach based on the principles of sustainable development can restore the well-being of the population and social and cultural life. Stable and sustainable development of cities and regions is based on the principles of sustainable development: development of sustainable mobility, and ensuring the inclusiveness of public spaces.

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References

[1] United Nations 1992 Rio Declaration on Environment and Development URL https://www.un.org/en/development/desa/population/migration/generalassembly/docs/globalcompact/A_CONF.151_26_Vol.I_Declaration.pdf
[2] United Nations 2015 Resolution adopted by the General Assembly on 25 September 2015. 70/1. Transforming our world: the 2030 Agenda for Sustainable Development URL https://www.un.org/en/development/desa/population/migration/generalassembly/docs/globalcompact/A_RES_70_1_E.pdf

[3] Ministry of Economic Development and Trade of Ukraine 2017 Sustainable Development Goals: Ukraine. National report URL https://www.kmu.gov.ua/storage/app/sites/1/natsionalna-dopovid-csr-Ukrainy.pdf
[4] Department of Strategic Planning and Macroeconomic Forecasting 2021 Sustainable Development Goals: Ukraine. Voluntary National Review URL https://ukraine.un.org/sites/default/files/2021-10/VNR%20SDG%20Ukraine%202020.pdf
[5] President of Ukraine 2019 Pro Tsili staloho rozvytku Ukrayiny na period do 2030 roku URL https://www.president.gov.ua/documents/7222019-29825
[6] Sachs J D, Kroll C, Lafortune G, Fuller G and Woelm F 2021 *Sustanable Development Report 2021: The Decade of Action for the Sustainable Development Goals. Includes the SDG Index and Dashboards* (Cambridge University Press) URL https://doi.org/10.1017/9781009106559
[7] Sachs J D, Kroll C, Lafortune G, Fuller G and Woelm F 2022 *Sustainable Development Report 2022: From Crisis to Sustainable Development, the SDGs as Roadmap to 2030 and Beyond* (Cambridge University Press) URL https://doi.org/10.1017/9781009210058
[8] The Legatum Institute Foundation 2020 *The Legatum Prosperity Index: A tool for transformation 2020* 14th ed (London: Legatum Institute) URL https://docs.prosperity.com/2916/0568/0539/The_Legatum_Prosperity_Index_2020.pdf
[9] Kuzmak O, Kuzmak O and Pohrishchuk B 2021 *E3S Web of Conferences* **255** 01035 URL https://doi.org/10.1051/e3sconf/202125501035
[10] Wendling Z A, Emerson J W, Esty D C, Levy M A, de Sherbinin A *et al.* 2018 *2018 Environmental Performance Index* (New Haven, CT: Yale Center for Environmental Law & Policy) URL https://epi.yale.edu/downloads/epi2018reportv06191901.pdf
[11] Schwab K and Zahidi S 2020 The Global Competitiveness Report Special Edition 2020: How Countries are Performing on the Road to Recovery Tech. rep. World Economic Forum Cologny/Geneva URL https://www3.weforum.org/docs/WEF_TheGlobalCompetitivenessReport2020.pdf
[12] Wolf M J, Emerson J W, Esty D C, de Sherbinin A, Wendling Z A *et al.* 2022 *Environmental Performance Index 2022: Ranking country performance on sustainability issues* (New Haven, CT: Yale Center for Environmental Law & Policy) URL https://epi.yale.edu/downloads/epi2022report06062022.pdf
[13] Dutta S, Lanvin B and Wunsch-Vincent S (eds) 2018 *The Global Innovation Index 2018: Energizing the World with Innovation* 11th ed (Ithaca, Fontainebleau, and Geneva: World Intellectual Property Organization, Confederation of Indian Industry) ISBN 979-10-95870-09-8 URL https://www.wipo.int/edocs/pubdocs/en/wipo_pub_gii_2018.pdf
[14] Dutta S, Lanvin B, León L R and Wunsch-Vincent S (eds) 2022 *Global Innovation Index 2022: What is the future of innovation-driven growth?* 15th ed (Geneva: World Intellectual Property Organization) ISBN 978-92-805-3433-7 URL https://www.wipo.int/edocs/pubdocs/en/wipo-pub-2000-2022-en-main-report-global-innovation-index-2022-15th-edition.pdf
[15] International Telecommunication Union 2014 Overview of key performance indicators in smart sustainable cities URL https://www.itu.int/en/ITU-T/focusgroups/ssc/Documents/Approved_Deliverables/TS-Overview-KPI.docx
[16] State Statistics Service of Ukraine 2022 Ukrayina u tsyfrakh 2021: statystychnyy zbirnyk URL https://ukrstat.gov.ua/druk/publicat/kat_u/2022/zb/08/zb_Ukraine%20in%20figures_21u.pdf
[17] Betlii O, Kravchuk V, Kostiv B, Kasperovych Y and Marianovych M 2022 Development finance assessment: Ukraine Analytical report UNDP URL https://www.undp.org/sites/g/files/zskgke326/files/2022-08/UNDP-DFAUkraineEN_v03.pdf
[18] Kolesnichenko O 2022 2.4 million Ukrainians lost their homes during the war. What about the promised housing from the state? URL https://www.epravda.com.ua/publications/2022/11/7/693516/
[19] World Bank, Government of Ukraine and European Commission 2022 Ukraine Rapid Damage and Needs Assessment, August 2022 Report Washington, D.C. URL http://web.archive.org/web/20230125202108/https://www.minregion.gov.ua/wp-content/uploads/2022/09/zvit-shvydka-oczinka-zavdanoyi-shkody-ta-potreb-na-vidnovlennya_-ukr-1.pdf
[20] World Bank, Government of Ukraine and European Commission 2023 Ukraine Rapid Damage and Needs Assessment : February 2022 - February 2023 Report Washington, D.C. URL http://documents.worldbank.org/curated/en/099184503212328877/P1801740d1177f03c0ab180057556615497
[21] Malolietkova O 2023 War causes colossal losses URL https://ukurier.gov.ua/uk/articles/vijna-zavdaye-kolosalnih-zbitkiv/
[22] Bechauf R 2022 The Value of Incorporating Nature in Urban Infrastructure Planning URL https://www.iisd.org/articles/insight/value-incorporating-nature-urban-infrastructure-planning

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Problems of the development of cultural tourism in the Carpathian region: the vision of consumers and service providers

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Problems of the development of cultural tourism in the Carpathian region: the vision of consumers and service providers

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Abstract. Tourism development in Ukraine has improved in terms of tourist flows, both as a diversification of tourism demand and tourism products in the last decades. Cultural tourism is a promising direction of tourist activity and occupies a leading position in the modern global tourist management system. The object of research is cultural tourism within the tourist destination of the Ivano-Frankivsk region. Regarding this, the authors revisit the phenomenon of cultural tourism in the country, in order to identify cultural tourism potential through cultural consumption among tourists, applying a special tourism survey. The purpose of this research is to identify the main problems of the development of cultural tourism in the Carpathian region from the point of view of demand and supply of cultural tourism programs based on the results of a comprehensive sociological study on the evaluation of tourist objects and the possibility of their inclusion in the cross-border tourist product “Carpathian Cultural Route”. The results of the survey demonstrated responses from 264 consumers of cultural tourism, which is 2,5% of the number of tourists (general population), and 140 respondents – employees of cultural institutions (objects of cultural tourism), the calculated sample of which was 28% of providers of cultural tourism services. The estimated sample was 28% of cultural tourism service providers. Among the positive aspects of the visit, tourists noted the price policy of institutions acceptable to them, the high level of authenticity and historical and cultural value of objects, the appropriate quality of service, and emotional comfort when visiting cultural and historical objects. According to consumers, the main problems of the development of cultural tourism are the low level of infrastructure support of objects and tourist destinations in general, the limited range of additional services, and limited information about the object. The authors emphasize the importance of developing culturally coherent policies to increase the competitiveness of tourist destinations. The most significant problems of the development of cultural tourism from the point of view of employees of tourist objects of cultural tourism are low level of infrastructure development of cultural tourist objects and tourist destinations in general, insufficient financing of institutions, low level of monetization of objects, low level of tourist and cultural activities in a tourist destination, insufficient advertising of the tourist object, imperfection of state tools for regulating tourist activity within cultural objects, low qualification of employees. Scientific developments on this topic will foster the application of innovative approaches towards the differentiation of cultural tourism objects, which, as a consequence, will help to target potential consumers and improve cultural tourism programs.

1. Introduction

Experts of the World Tourism Organization have identified the five most promising types of tourism in the 21st century, among which cultural tourism occupies an important place. Recently, the UNWTO confirmed [1] that cultural tourism is the main element of international tourism consumption, accounting for more than 39% of tourism incomes.

Cultural tourism research is developing rapidly, particularly in areas such as cultural consumption, cultural motives, heritage conservation, the economics of cultural tourism, anthropology, and relations with the creative economy. Major research trends include a shift from tangible to intangible heritage as a tourism resource, greater attention to indigenous and other minority groups, and a geographic expansion of cultural tourism research [2]. In the allocation of cultural tourism as a specific sector in the tourism system, a combination of the characteristics of tourist demand in cultural tourism is considered, which consists in acquiring new experiences and impressions to ensure cultural needs and the characteristics of offers – special tourist resources that are involved in the process of satisfying demand in the field of cultural tourism [3].

Cultural is recognized as one of the main resources used to counteract seasonality in tourist destinations, being by its very nature non-seasonal. Promoting cultural tourism is just one component for effectively counteracting seasonality [4]. Research on the demand for cultural tourism, as a rule, shows the differentiation of the market. The study of the demand for cultural tourism, as a rule, indicates the differentiation of the market. Thus, the authors substantiate the importance of studying the demand for cultural tourism on the example of a number of Asian countries. Location-based social media data provides information on the observed behavior of tourists, which is considered more progressive than traditional surveys that collect spoken responses from tourists. Scientists also classify cultural tourism attractions on the basis of tourists' preferences revealed by their travel trajectories [5].

The theoretical and methodological aspects of the development of tourism are highlighted [6], the thesis that cultural tourism is a means of forming national identity, that is, it fulfills an important humanitarian and state-building mission, is a means of education and enlightenment, is substantiated. Community Cultural Development methods can enhance community capacity and the sustainability of tourism by increasing residents' effective participation in decision-making, encouraging locals' partnership in, and ownership of, tourism projects, and providing space for negotiating the tourist gaze in guest-host relationships [7]. Also, World cultural heritage is of great significance in promoting the sustainable development of cities, and history culture is very important to achieve the goal of sustainable development [8]. Regional studies of cultural tourism relate to the resource base, the search for potentially attractive tourist locations that have cultural value and will contribute to the creation of a positive image of the tourist destination, directions for future actions, ideas, and projects that will help realize the strategic vision of the development of cultural tourism [9–12]. The scientific developments of Ukrainian scientists in the field of cultural tourism relate mainly to the methodologies of the organization of cultural tourism and the justification of the development of cultural tourism at the regional level. Modern trends in the development of cultural tourism in Ukraine were analyzed using the example of Lviv and Kamianets-Podilski as the most popular tourist destination in Ukraine [13]. However, the scientific publications do not cover issues related to the analysis of the problems of the development of cultural tourism in Ukraine through the prism of demand and supply in the market of tourist services.

The *purpose* of the research is to outline the main problems of the development of cultural tourism in the Carpathian region from the point of view of demand and supply of cultural tourism programs based on the results of comprehensive sociological research on the evaluation of tourist objects and the possibility of their inclusion in the cross-border tourist product "Carpathian Cultural Route".

The *task* of the research is to analyze the results of the research on the demand for cultural tourism through surveys of tourists who visit cultural tourism objects and tourist objects of cultural tourism (tourist offer of cultural tourism) by surveying the management staff of institutions regarding the problems of the development of tourist objects of cultural tourism.

The *subject* of research is the development of cultural tourism through the prism of the analysis of demand and supply in the market of cultural tourism in the Ivano-Frankivsk region.

The *object* of research is cultural tourism within the tourist destination of the Ivano-Frankivsk region. The scientific novelty of the research consists in substantiating the problems and prospects of the development of cultural tourism based on the analysis of the results of consumer research on cultural tourism service providers on the example of the development of cultural tourism in the Ivano-Frankivsk region.

2. Materials and methods

Cultural tourism deals with the main components of natural and cultural heritage. These are special cultural landscapes, and architectural monuments, and museums of various types, and historical cities and settlements, and archaeological excavations, and crafts, and holidays, and also national cuisine.

National cultures are a powerful motivator of tourism. The Ukrainian Cultural Foundation considers cultural tourism as a powerful tool not only for spreading information about the country's cultural heritage, preserving it to maintain a high level of attractiveness, but also as a good tool for its monetization and increasing its role in the socio-economic development of communities [14]. Scientists confirm that cultural tourism should be considered as a powerful factor in the development of countries and regions. For example, the cultural and tourism policies of 101 countries of the world were analyzed countries and found that countries that significantly support cultural heritage have more significant success in tourism, especially inbound tourism [15]. The interaction of tourism and cultural heritage can become a factor in increasing the competitiveness of countries in the tourism market. Scientists offer a cultural explanation of the competitiveness of travel and tourism of countries by studying the relationship between the competitiveness of tourist destinations and interest in the national culture of the countries of tourist arrivals [16]. Direct correlations were revealed by analyzing data from 73 countries. The authors emphasize the importance of developing culturally coherent policies to increase the competitiveness of tourist destinations [17]. The introduction of innovations in the field of cultural tourism is also an urgent scientific problem. Heritage tourism destinations are facing the challenge of realizing innovative development based on cultural inheritance conservation [18]. Specifically, the article analyzes the effect of two contingent environmental factors, namely competitive intensity and technological dynamism, on the relationship between innovation capability and pioneering orientation in hospitality and tourism firms. The results show that innovation capability is a key antecedent of pioneering orientation in hospitality and tourism firms [19]. Technologies that require visitors' active participation afford opportunities for verbal and physical interactions with other visitors. By contrast, passive technologies, providing recreational and artistic content to visitors without them having to interact with the technology, tend to preclude social interactions [20].

The original, preserved authentic material and immaterial culture of certain ethnographic regions, for example, Hutsulshchyna, Pokuttya, Boykivshchyna became a magnet for many visitors from Ukraine and foreign tourists. However, the number of tourist arrivals, in accordance with the available cultural tourism attractions, can be much higher, because cultural and educational is the main motivation for visits to the Ivano-Frankivsk region [21]. Different types of tourism are developing in the region, and accordingly, a network of enterprises serving the tourism sphere [22]. But it is necessary to take into account that the development of tourist activity should be regulated taking into account the prevention of overtourism and damage to the environment. The result of uncontrolled infrastructure development, the growth of mass unregulated visits to famous cultural and natural complexes can have a negative impact on destinations, as well as on the local socio-cultural environment [23–25]. To identify problems and ways to improve cultural tourism, the opinion of providers of cultural tourism services (cultural institutions) and consumers of these tourist services is important, which is the basis for developing development strategies and conducting an active promotional policy of cultural objects. For this purpose, a comprehensive study was conducted, part of which was a survey of tourism entities that provide cultural tourism services and visitors to cultural tourism objects.

Questionnaire survey (questionnaire) is the most popular method of quantitative sociological research. Questionnaire surveys for sociological marketing research are most in demand today. You can get information with the help of a survey, which is not always reflected in documentary sources or available for observation. Therefore, a field survey was chosen as the main research method. This approach refers to a methodological procedure that collects data from a selected group of respondents in the areas where the respondents are currently located, namely at the workplace and during customer visits to the objects. In this way, responses were received from consumers and providers of cultural tourism services. This method is effective in cases where the source of information is directly the participant-carrier of information (in our case, the management of institutions and visitors of objects). This method is still the only one available in this case due to the lack of other systematic statistical data of this kind, despite the criticism [26].

A sample of 2,5% of respondents from the general population is sufficient to obtain representative information. The volume of the general population is determined by the authors according to the number of cultural institutions in the research region and is about 500 institutions, which include, in addition to cultural and historical objects with protection status (including local ones) and other institutions, for example, private tourist attractions and museums, that is, institutions that actually provide cultural tourism services. From the compiled database of establishments, those that are most popular and those located along and near the cross-border highways Lviv-Rohatyn-Ivano-Frankivsk-Yaremche-Rakhiv-Solotvyno and Lviv-Halych-Ivano-Frankivsk-Kolomiya-Kosiv-Verkhovyna. Questionnaires were offered to 154 respondents-cultural institutions, information was received from 140 objects. The calculated sample was 28%, which allows us to assert the representativeness of the survey within the studied region.

Two hundred and sixty-four people took part in the questionnaire. The sample for which the study was conducted included persons representing the adult population (over 18 years old) by gender, age, and education.

This number of respondents was 2,5% of the number of tourists (general population) who were served by travel agents and tour operators in the Ivano-Frankivsk region in 2020 [27]. The respondents filled out the questionnaire immediately on the spot, which guaranteed their complete return and, in addition, the researcher was able to be present when filling out the questionnaires, helping the respondents by clarifying certain questions.

Questionnaires with a small number of questions to the respondents were formed in order to get answers more guaranteed. These are structured questions about the main characteristics of the institution, its activities, outlined problems and prospects for their development. Sample field surveys were conducted during the "low" tourist season – September – November – 2021 in the objects of visits – tourist objects of cultural tourism and visitors of these institutions.

3. Results

The survey of consumers of cultural tourism services showed a number of positive and negative impressions made on them by tourist objects of cultural tourism, features of tourist services in them and within tourist destinations. Tourists noted the acceptable for them price policy of institutions among the positive aspects of the visit. 53,8% of tourists indicated a high rating of "excellent", 31,8% – "good", 8% – "satisfactorily", and 5,3% of respondents didn't answer the question (figure 1).

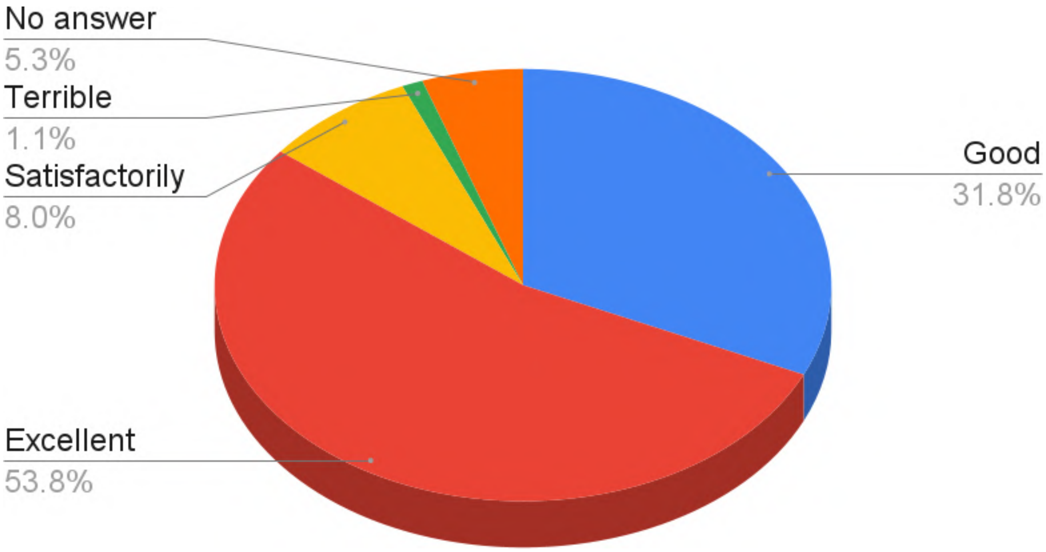

Figure 1. Distribution of respondents' answers regarding price policy when visiting cultural and historical objects.

62,9% of respondents gave the answer "excellent" regarding the assessment of the authenticity (uniqueness) of cultural and historical objects, 25,8% – "good", 7,6% – "satisfactorily", 1,1% – "badly", 2,6% – no answer (figure 2).

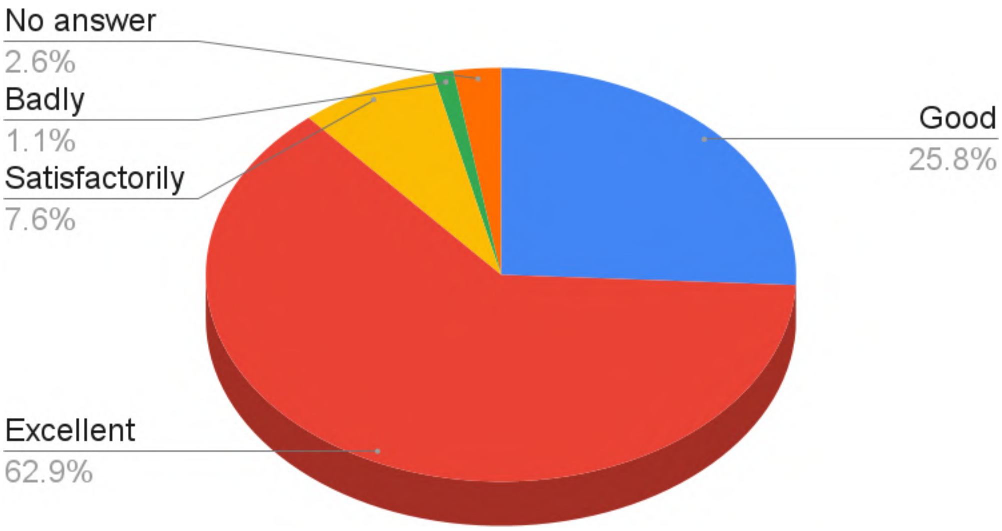

Figure 2. Assessment of the authenticity of cultural and historical objects.

According to the state of preservation of tourist objects as a cultural and historical value, 65,2% of surveyed tourists rated it as "excellent", 23,5% – "good", 8,3% – "satisfactorily", 2,2% – didn't indicate the answer to the question and less than 1% – "badly" (figure 3).

The quality of service when visiting cultural and historical sites in Ivano-Frankivsk and Transcarpathian regions was assessed as "excellent" by 59,8% of respondents, "good" by 25,8%

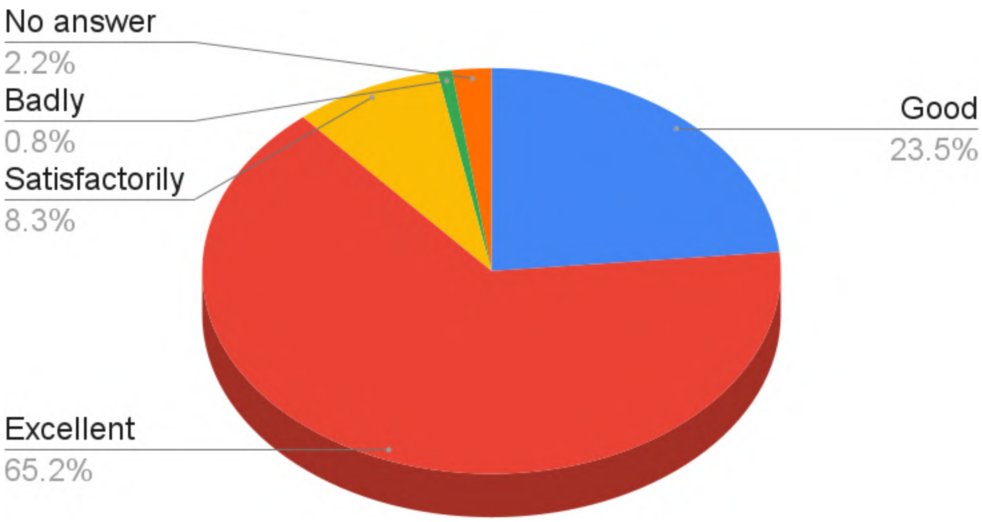

Figure 3. Assessment of the cultural and historical value of tourist objects.

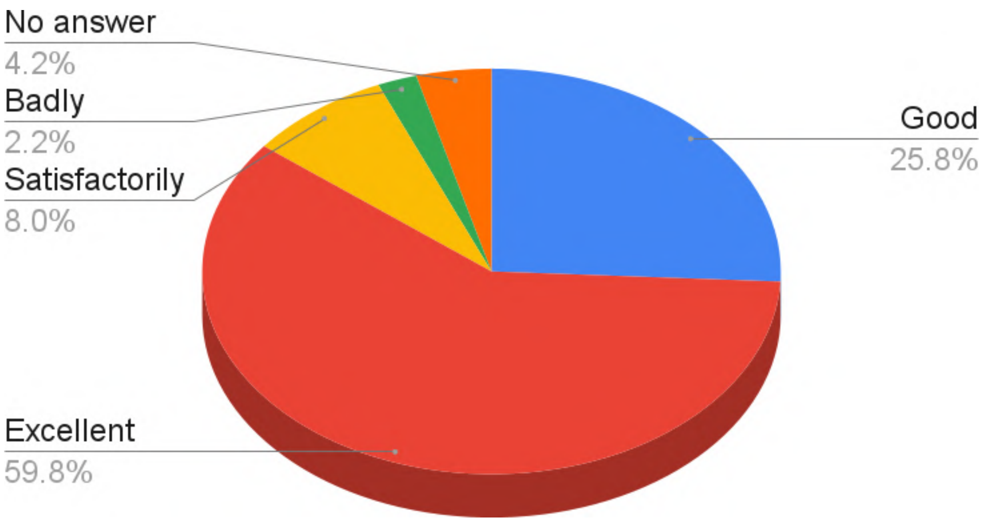

Figure 4. Assessment of the quality of service when visiting cultural and historical objects.

of tourists, 8% – "satisfactorily", 2.2% – "badly", 4,2% of visitors did not indicate the answer to the question (figure 4).

The largest number of tourists (70,1%) scored "excellent", 18,6% – "good", and 7,6% – "satisfactorily" according to the parameter "Emotional comfort". This indicates a positive general impression when visiting tourist locations in the Carpathian region (figure 5).

Most of the tourists (37,9%) rated the recreation infrastructure of the territory, where cultural and historical objects are located, as excellent, 34,1% – "good", 18,9% – "satisfactorily", 4,2% – no answer, the remaining 4,9% of visitors were dissatisfied with the arrangement of the rest area near tourist locations (figure 6).

Respondents quite positively assessed the availability of information when visiting cultural and historical objects: 35.2% of respondents rated it as "excellent", 29.2% – "good", 24.2% – "satisfactorily", 5.7% – provided no answers, 5.7% – of surveyed tourists were dissatisfied with information accessibility to tourist facilities (figure 7).

Territorial accessibility when visiting cultural and historical objects was rated as "excellent"

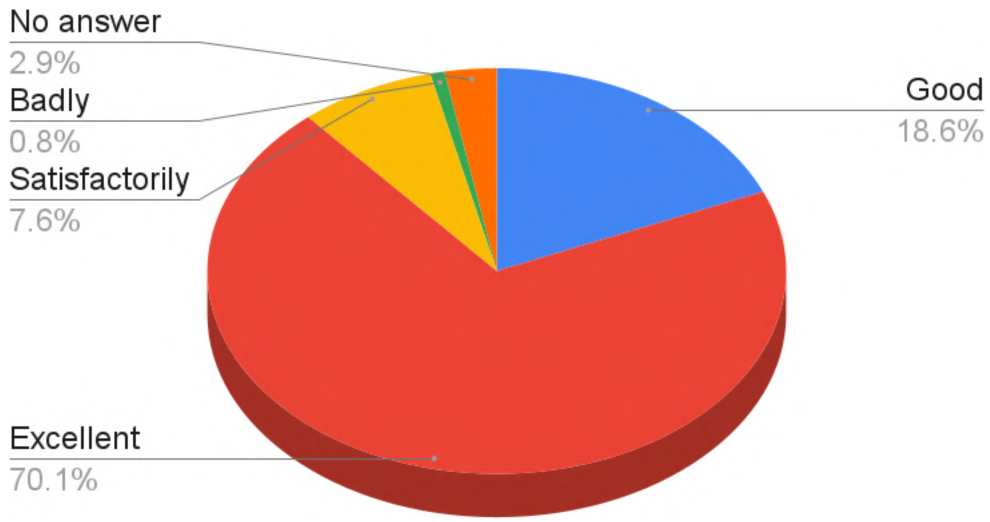

Figure 5. Assessment of emotional comfort when visiting cultural and historical objects.

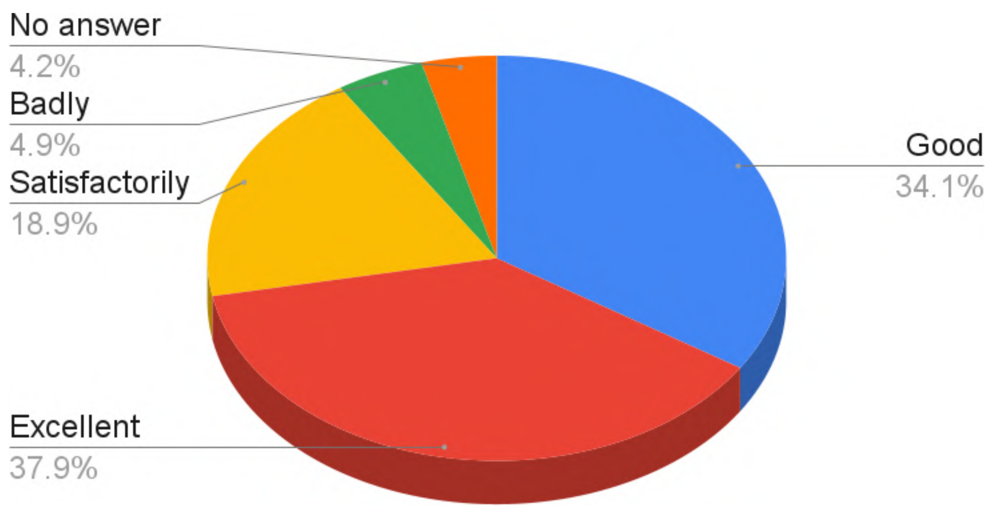

Figure 6. Assessment of the recreational infrastructure of the territory where cultural and historical objects are located.

by 50,8% of tourists from the total sample of all respondents, "good" – 30,7%, "satisfactory" – 14%, "badly" – 1,1%, 3,4% of respondents did not indicate the answer to the question (figure 8).

47,3% of respondents rated the attractiveness of cultural and historical objects of Ivano-Frankivsk and Transcarpathian regions as "excellent", 37,9% – "good", 9,5% – "satisfactorily", 0,8% – "badly" and 4,5% of tourists did not answer the question (figure 9).

Natural objects (mountains, waterfalls), the historical value of cultural heritage objects, and architectural monuments of the research area made the most positive impression on visitors (figure 10).

Tourists faced a number of problems when visiting cultural and historical objects of the Carpathian region, among which the most significant are:

1. **Low level of infrastructural support of objects and tourist destinations in general.** The majority of respondents (15%) indicated that a significant drawback is the poor condition of the roads, which makes it difficult for vehicles to move. The surveyed

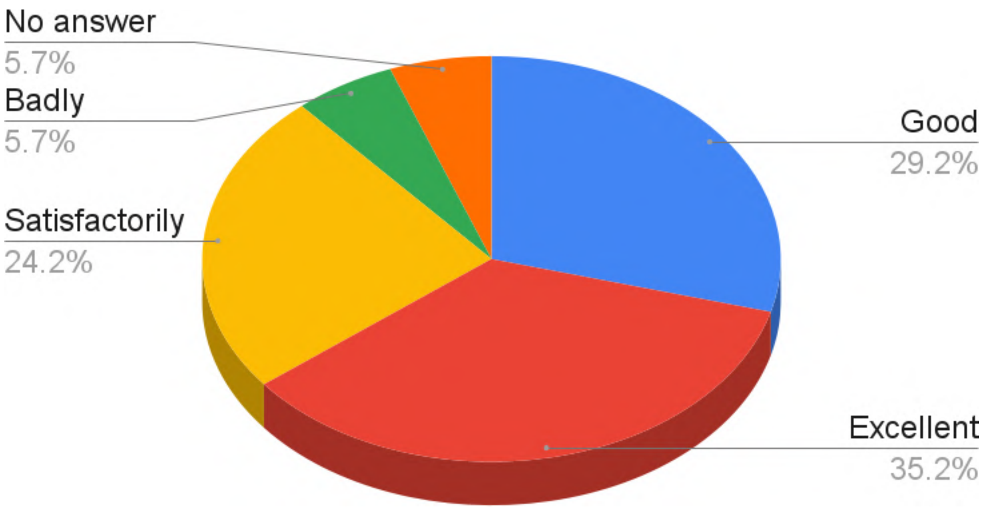

Figure 7. Assessment of information availability when visiting cultural and historical objects.

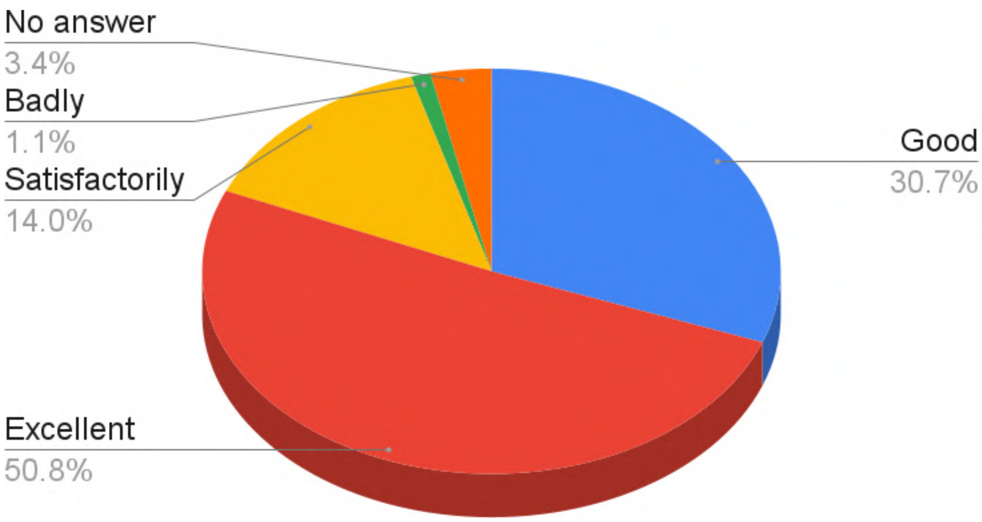

Figure 8. Assessment of territorial accessibility when visiting cultural and historical objects.

tourists noted those services determined by the development of infrastructure and the lack of which causes the greatest discomfort, among them: limited access to the Internet (9,5%), lack of food establishments (8,5%), insufficiently developed transport connections (10,9%), littered territory (6,3%), inaccessible mobile communication (5,1%). The discrepancy between the price and the quality of services (3,2%), unfriendly service staff (1,7%) and the danger of some historical objects (ruins) (1%) was also noted (figure 11).

2. **Limited range of additional services.** A significant part of the surveyed tourists (13,8%) indicated the limited range of services at the object, 11,7% – the absence of cultural and entertainment institutions.
3. **Limited information about the object.** 13.3% of respondents indicated limited information about the object, despite the rather high level of information availability on the cultural object. Almost a quarter of respondents (24.3%) received information about interesting tourist locations from acquaintances, 12.8% – obtained information from social networks, 10.3% – a previous visit, 8.5% – information provided to tourists in travel agencies

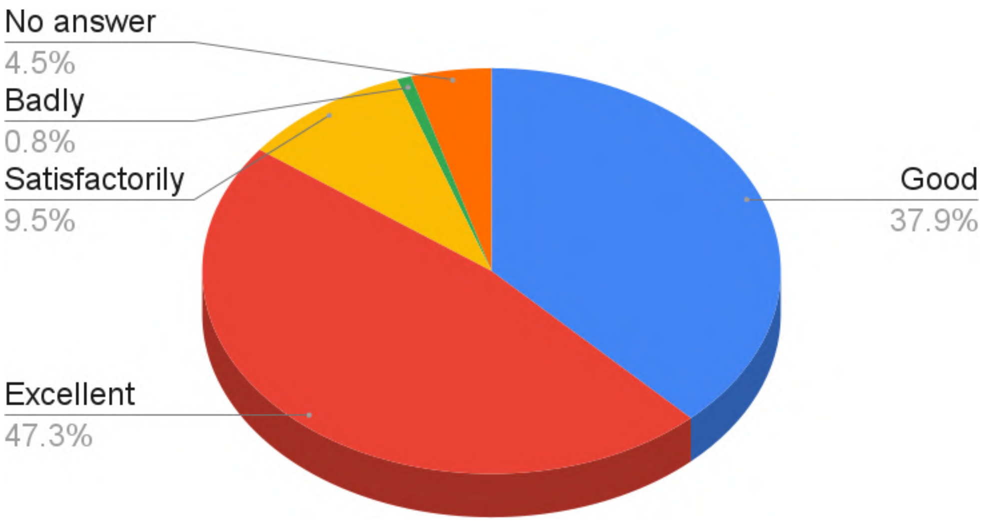

Figure 9. Assessment of the attractiveness of cultural and historical objects.

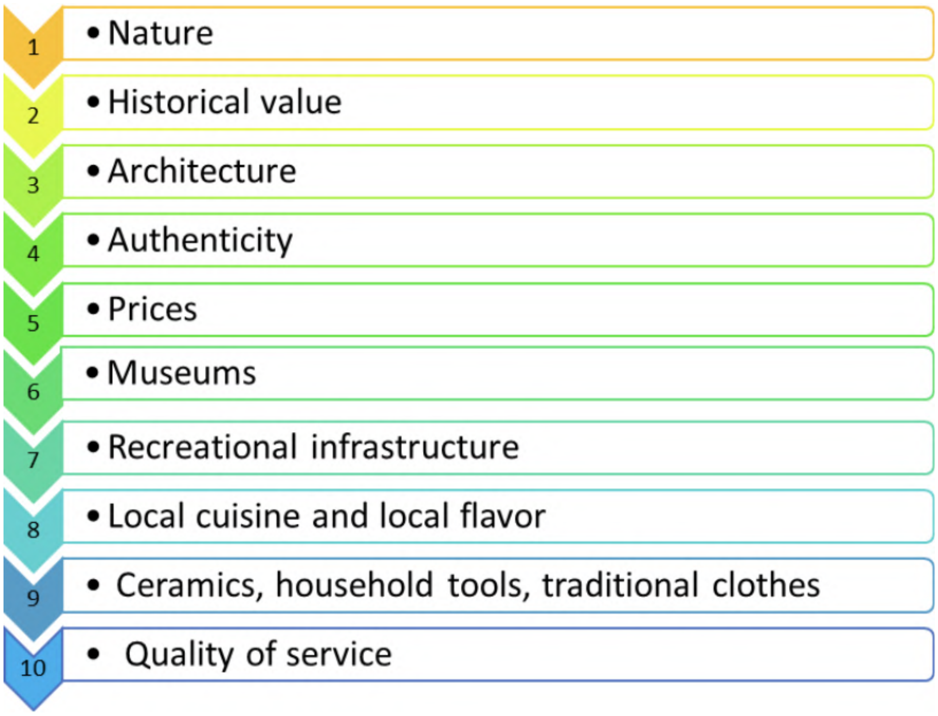

Figure 10. Top 10 answers of the respondents to the question "What did you like most about the object of the visit?"

, 5.2% – other (banners, YouTube), 2.7% of respondents use books, guidebooks, magazines, booklets to obtain information about recreation opportunities, 2.4% – tourist information centers, 2.4% – mass media and 0.6% – exhibitions and fairs.

Only 27% of the respondents from the total sample of those interviewed left comments and expressed suggestions for improving the attendance of cultural and historical objects in the research territory during the sociological research. This is very valuable information that can be used in the work of cultural objects to improve their activities. Although the suggestions were

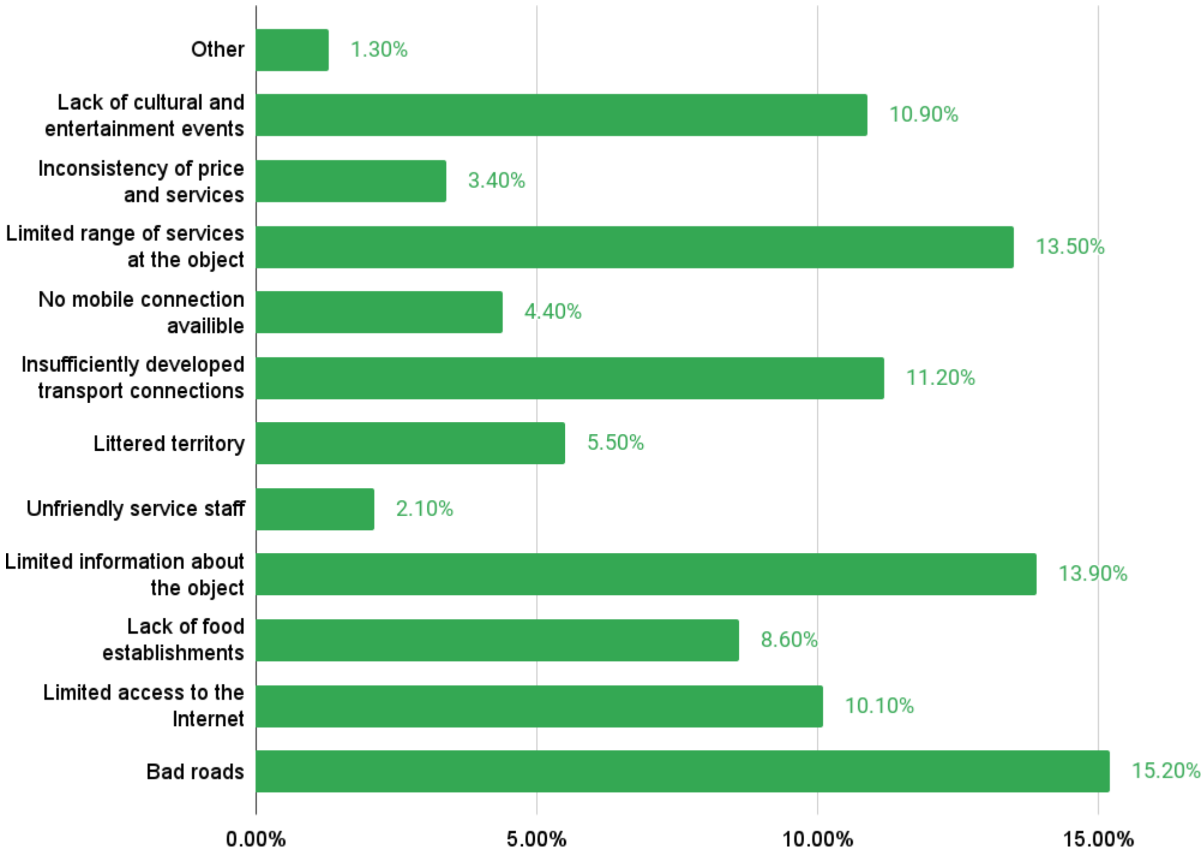

Figure 11. Distribution of respondents' answers to the question "What problems did you encounter when visiting a cultural and historical object?"

expressed by a small number of respondents, we can say that the advice was given by consumers who have experience in tourist trips, who support the development of culture and tourism and can formulate their vision of problems and ways to solve them. Respondents noted the following directions for improving recreation: improving infrastructure (22,2%) and beautification of the territory (18,5%), attracting sponsors for the restoration of cultural heritage (11,1%), restoration of cultural and historical objects (11,1%), information provision (7,4%), public toilets (3,7%), cultural and entertainment events (3,7%) (figure 12).

During the survey of employees of cultural tourism facilities, a number of problems were outlined, which the respondents noted as barriers to the development of tourism activities. Among the institutions most mentioned by employees are:

1. **Low level of infrastructure development of the cultural tourist object and the tourist destination in general.** The level of development of tourist infrastructure, which is the basis of tourist activity, was assessed by 63,2% of respondents as underdeveloped and indicated this factor as a significant barrier in the development of a tourist cultural object. A detailed analysis of the infrastructure will be provided in our next publications.
2. **Insufficient financing of institutions.** 59,6% of respondents pointed to the insufficient amount of finance for the development of tourist objects. More than 78,6% of respondents indicated the need for two or more sources of financing. 75,9% of respondents noted that their own funds earned in the process of tourist activity are a source of income. Respondents also see a solution to the problem of underfunding in participation in grant programs (14,8%).

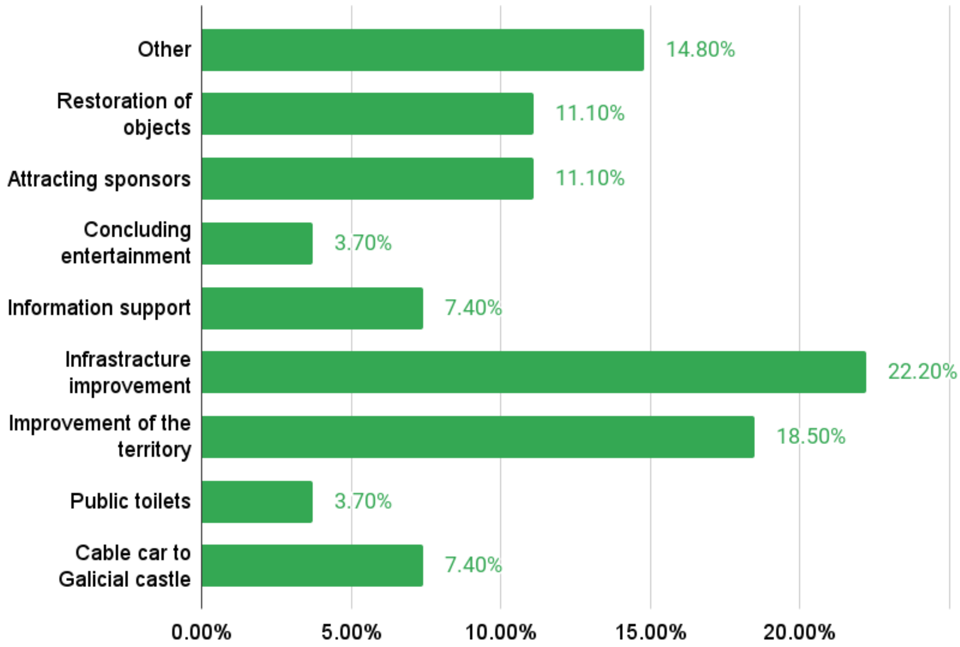

Figure 12. Distribution of respondents' answers regarding improvement of recreation in Ivano-Frankivsk and Transcarpathian regions.

On the other hand, the survey of consumers showed that they are ready to spend additional funds within the framework of visiting cultural objects. Almost a quarter of respondents (24.7%) are ready to spend additional money on souvenirs, 18.5% of respondents – on entrance tickets to museums, 12.6% of respondents – on organized excursions, 9.5% – on festivals, 7.2% – master classes, 7% – entertainment events. Only 2% to 5% of tourists spend additional money on concerts, performances, shopping, SPA and donations in churches (figure 13).

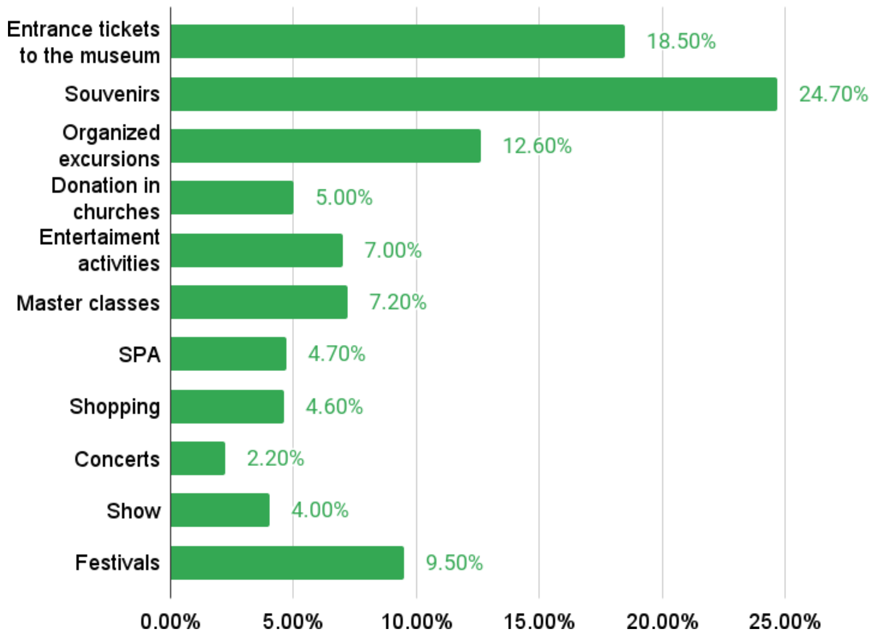

Figure 13. Potential expenses of tourists at cultural tourism objects.

3. **Low level of monetization of objects.** The problems of financing the activities of the objects and the low level of their monetization are related to each other. The low price for visiting the objects (free visiting in 52,2% of the objects), and the lack of excursion programs (17,6% of respondents) prevent the development of the object as a tourist attraction. 52,2% of respondents also agree with the thesis about the insufficient number of attractions within the objects, which makes it impossible to diversify tourist services and increase income.
4. **Low level of tourist and cultural activities in the tourist destination.** 50,7% of respondents – tourist objects point to the insufficient number of cultural events that are held in tourist destinations, three quarters – to the readiness to join these events. Public-private partnerships in this area, combining the efforts of cultural and tourism institutions can be the key to revitalizing both tourism and culture. 84.6% of respondents are ready to take part in the developed tourist programs for the activation of tourist activities at cultural tourism objects (figure 14).

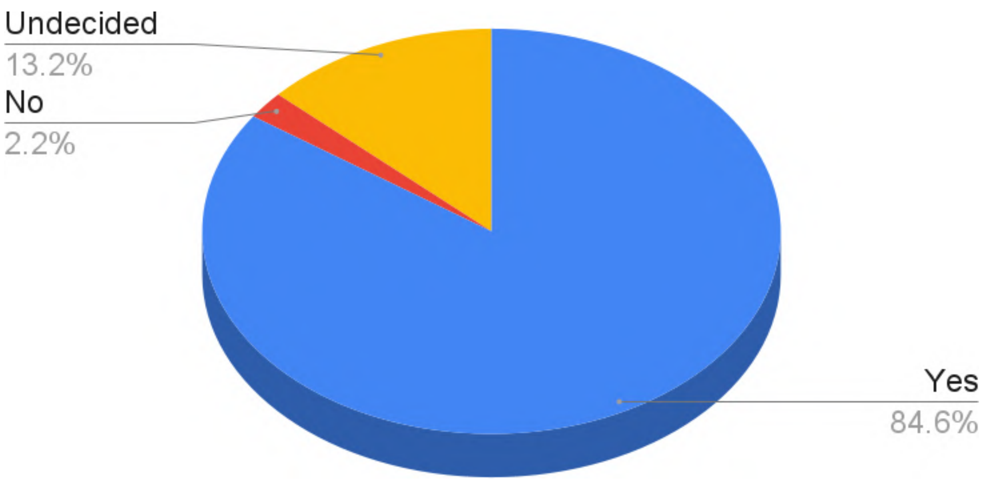

Figure 14. Readiness of respondents to participate in tourist programs.

5. **Insufficient advertising of the tourist object.** 26,5% of respondents agree with the thesis about insufficient advertising of the cultural object.
6. **Imperfect state tools for regulating tourist activity within cultural objects.** Imperfect legislation and high tax pressure in this field were indicated by 16,1% and 11% of respondents, respectively, as a problem in the development of tourism. This answer was mainly given by private craft traditional productions, private museums, and museums that do not belong to the Ministry of Culture of Ukraine.
7. **Low qualification of employees.** 8,8% and 8,1% of respondents indicated the low qualification of employees and the low quality of services as a barrier to the development of tourist objects. However, the respondents, in general, are open to gaining new experience and knowledge about tourist activities at the objects of historical and cultural heritage: 73,5% of respondents are ready to participate in training within the framework of projects of this direction, 11,8% did not answer this question, 13,2% of respondents were undecided on this issue, 1,5% of respondents answered this question negatively (figure 15).

In general, 72% of respondents clearly outlined the ways to solve the problems of the development of cultural objects as tourists. However, 28% of respondents did not formulate their own problems, which became barriers to development and obviously do not work on their solution (figure 16).

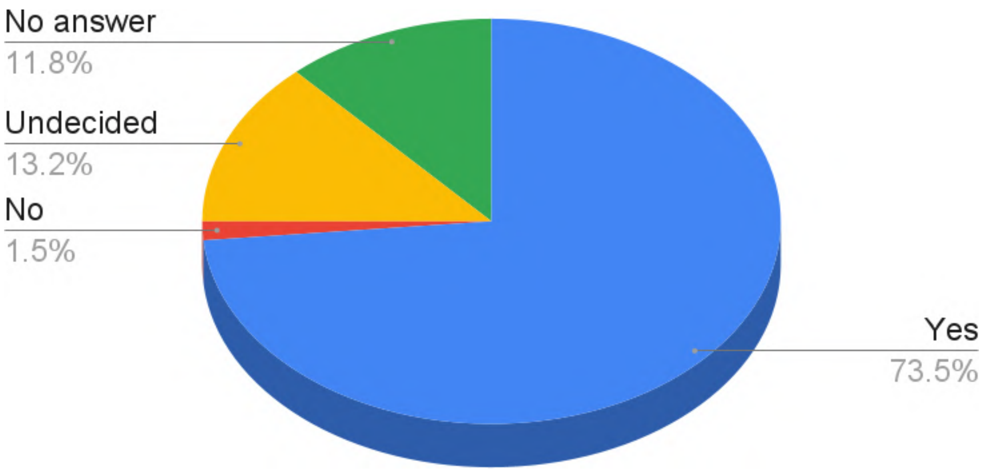

Figure 15. Readiness of respondents to participate in training as part of projects.

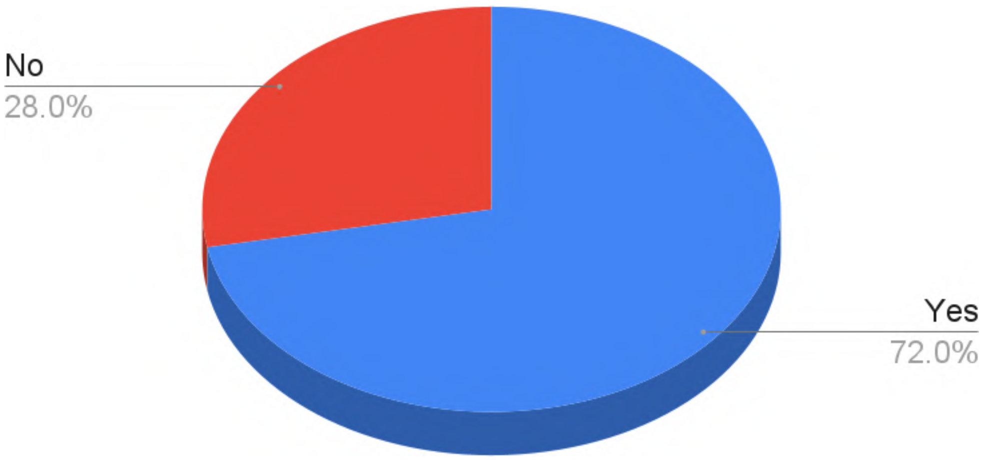

Figure 16. Distribution of respondents' answers regarding the question "Are you aware of ways to solve your problems in the development of tourist objects?"

4. Conclusions

Ukraine is attracting increased interest in the world. Our country has become a symbol of courage and stability. Ukraine was considered "terra incognita" in past years from a tourist point of view, so experts predict an increase in tourist visits after the war. The analysis of literary sources on cultural tourism revealed a certain lack of coverage of the problems of the development of cultural tourism from the point of view of the consumer and the service provider. Studying the problems of cultural tourism development through the prism of supply and demand is the most informative and reliable way, according to the authors, which allows taking into account the opinions of producers and consumers of cultural tourism services.

From the point of view of applying a group of research methods, according to the authors of the article, obtaining voluntary information from persons who are involved in the work of a tourist object of cultural tourism is the most accurate, as it includes an expert assessment of persons who have certain qualifications, experience and are constantly present on the object. Obtaining information from tourists visiting cultural objects allows you to reach the consumers of cultural tourism, that is, its target audience. Elaboration of the results of the survey of consumers and providers of cultural tourism services made it possible to identify the problems that were noted by two groups of respondents. Among the most relevant are the unsatisfactory state of roads and tourist infrastructure in general, the low level of dissemination of information about cultural tourism objects, the lack of additional services at the cultural tourism object, etc. The research of a wide range of problems of demand and supply in cultural tourism will allow for the improvement of cultural tourism programs, identify its target audience, offer ways to improve the resource potential of cultural tourism, etc. The scientific developments of this subject should contribute to the application of innovative approaches to the differentiation of cultural tourism attractions, which helps to orientate potential tourists.

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References

[1] UNTWO 2020 International tourism growth continues to outpace the global economy URL https://www.unwto.org/international-tourism-growth-continues-to-outpace-the-economy
[2] Richards G 2018 *Journal of Hospitality and Tourism Management* **36** 12–21 ISSN 1447-6770 URL https://doi.org/10.1016/j.jhtm.2018.03.005
[3] Kermani A A 2022 Future Making in the Anthropocene Blog — Mass tourism in historical cities URL https://heritagetribune.eu/europe/future-making-in-the-anthropocene-blog-mass-tourism-in-historical-cities/
[4] Vergori A S and Arima S 2020 *Journal of Hospitality and Tourism Management* **78** 104058 URL https://doi.org/10.1016/j.tourman.2019.104058
[5] Liu Z, Wang A, Weber K, Chan E H W and Shi W 2022 *Journal of Hospitality and Tourism Management* **90** 104488 URL https://doi.org/10.1016/j.tourman.2022.104488
[6] Timothy D J 2018 *Tourism Management Perspectives* **25** 177–180 URL https://doi.org/10.1016/j.tmp.2017.11.018
[7] Moayerian N, McGehee N G and Stephenson M O 2022 *Annals of Tourism Research* **93** 103355 URL https://doi.org/10.1016/j.annals.2022.103355
[8] Zhang S, Lin J, Feng Z, Wu Y, Zhao Q, Liu S, Ren Y and Li H 2023 *Journal of Urban Management* **12**(2) 96–111 ISSN 2226-5856
[9] Yu X and Xu H 2019 *Journal of Destination Marketing & Management* **13** 39–50 URL https://doi.org/10.1016/j.jdmm.2019.05.003
[10] Liu S T 2020 *Journal of Destination Marketing & Management* **16** 100432 URL https://doi.org/10.1016/j.jdmm.2020.100432
[11] Stratan A, Perciun R and Gribincea C 2015 *Procedia - Social and Behavioral Sciences* **188** 116–121 URL https://doi.org/10.1016/j.sbspro.2015.03.346
[12] Arkhypova L M, Korobeynikova Y, Kachala S, Vinnychenko I, Pobigun O and Hryniuk V I 2022 *Journal of Geology, Geography and Geoecology* **31**(2) 199–210 URL https://doi.org/10.15421/11223701
[13] Uliganets S, Arion O and Bol D 2018 *Bulletin of Taras Shevchenko National University of Kyiv. Geography* **72**(3) 77–78 URL https://doi.org/10.17721/1728-2721.2018.72.13
[14] Posypanko D 2020 Kulturnyi turyzm – neprosti vidnosyny URL http://dialog.lviv.ua/kulturniy-turizm-neprosti-vidnosini/
[15] Chen H and Rahman I 2018 *Tourism Management Perspectives* **26** 153–163 URL https://doi.org/10.1016/j.tmp.2017.10.006
[16] Lee C C, Chen M P and Xing W 2022 *Economic Analysis and Policy* **74** 666–686 URL https://doi.org/10.1016/j.eap.2022.03.021
[17] Kumar S and Dhir A 2020 *Journal of Destination Marketing and Management* **18** 100501 URL https://doi.org/10.1016/j.jdmm.2020.100501
[18] Wang M Y, Li Y Q, Ruan W Q, Zhang S N and Li R 2023 *Journal of Hospitality and Tourism Management* **55** 118–130 URL https://doi.org/10.1016/j.jhtm.2023.03.009
[19] Ruiz-Ortega M J, García-Villaverde P M, Gala-Velásquez B D L, Hurtado-Palomino A and Ángela Yuliana

Arredondo-Salas 2021 *Journal of Hospitality and Tourism Management* **48** 441–450 URL https://doi.org/10.1016/j.jhtm.2021.07.012

[20] Ponsignon F and Derbaix M 2020 *Tourism Management Perspectives* **35** 100723 URL https://doi.org/10.1016/j.tmp.2020.100723

[21] 2018 Kompleksne analityko-praktychne sotsiolohichne doslidzhennia sotsialno-demohrafichnoho profiliu odnodennykh vidviduvachiv (ekskursantiv) ta turystiv Ivano-Frankivskoi oblasti (2018) URL https://www.if.gov.ua/turizm/analitika-i-sociologiya-tourism

[22] Cabinet of Ministers of Ukraine 2017 Strategy for the development of tourism and resorts for the period up to 2026 URL https://zakon.rada.gov.ua/laws/show/168-2017-%D1%80

[23] Iuras I, Raiter P, Korobeinykova Y and Poberezhna L 2020 *Ecological Questions* **31** 63–69 URL https://doi.org/10.12775/EQ.2020.014

[24] Al shawabkeh R, AlHaddad M, al_fugara A, Arar M, Alhammad R, alshraah M and alhamouri M 2023 *Alexandria Engineering Journal* **69** 639–676 ISSN 1110-0168 URL https://doi.org/10.1016/j.aej.2023.02.001

[25] Liu Y, Wang Y, Dupre K and McIlwaine C 2022 *Tourism Management Perspectives* **43** 100994 URL https://doi.org/10.1016/j.tmp.2022.100994

[26] Brannen J 1992 *Mixing Methods: Qualitative and Quantitative Research* (London: Routledge) URL https://doi.org/10.4324/9781315248813

[27] Regional Department of Statistics in Ivano-Frankivsk region 2021 Kolektyvni zasoby rozmishchuvannia (yurydychni osoby, vidokremleni pidrozdily yurydychnykh osib) URL https://ifstat.gov.ua/EX_IN/T4_1.HTM

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Ecofacilitative pedagogy as a form of sustanability and social therapy

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Ecofacilitative pedagogy as a form of sustanability and social therapy

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Abstract. This article raises the question of the role of non-formal and hybrid education as a form of personal and social sustainability in the war-time adversity. The authors attempt to estimate the role of the eco-facilitation course as one of the original Ukrainian approaches to psychological assistance. The course was provided to different categories of students (displaced and relocated within Ukrainian borders or with a refugee status in Europe and USA). It was found that experimental training by the method of ecofacilitative teaching contributes to individual and social sustainability in terms of rhythmic development (thesis-antithesis-synthesis). In particular, the changes in pedagogy reflect the logic of their non-directive teaching (ecofacilitation). Ecofacilitation is an educational course aimed at developing skills for sustainable self-development or personal stabilization in conditions of instability and chaos, which closely corresponds to the living conditions of an individual during wartime.

1. Introduction

The psycho-emotional state of people during the war in Ukraine, in situations of high and prolonged uncertainty, is characterized by a significant degree of dynamism, variability, the so-called "psychological swing" when the resource, conscious and active condition is abruptly replaced by exhaustion, loss of meanings and guidelines. In this regard, the search for effective individual and group forms of a non-clinical, psychological and pedagogical nature is actualized. These forms could be viewed as such that ecologically, consistently and rapidly contribute to the stabilization of the personality at various stages of its development in adversity. Such flexible, often hybrid forms and technologies have a high, in a sense, universal stabilization potential empowered by psychological and pedagogical mechanisms of ensuring a sustainable future. The formation of an ecological attitude towards the environment is carried out through pedagogical and psychological influence on an individual. In the context of our research, these two disciplines are combined under the concept of social therapy as a condition for the formation of an adequate attitude towards the environment.

2. Psychological markers of the war in Ukraine. Pedagogical research to psychological sustainability: literature review

A number of studies reflect the negative experiences of the considerable part of the population, which are determined by a radical change in a lifestyle – forced immigration, displacement to other regions, loss of loved ones [1–3], a significant reduction in social programs including medicine, the need to overcome migration stress, such as unemployment, poverty, food insecurity, social exclusion and housing difficulties, etc. [4–6].

Another group of studies shows that along with, or as a result of, a radical change in socio-psychological conditions, the population of Ukraine, for the first time within decades, encountered a number of positive phenomena – such as cohesion [7] activation of hidden psychological and social mechanisms of self-regulation [8]; even a certain level of well-being, including psychological, physical, social [9]; various determinants of resilience, both individual and collective [10].

In studies devoted to the problems of sustainable development or spontaneous system's stabilization in critical periods (COVID-19), the authors come to conclusions (a) about the emergence of spontaneous and rhythmic personality stabilization such as "thesis-antithesis-synthesis" (immunity/or protective socio-psychological regulation can manifest itself in terms maintaining a certain rhythm of development, accompanied by signs of spontaneous resistance, well-being and tolerance to uncertainty) [11,12]; (b) that not only in the context of the pandemic, but also at various stages of military aggression, the Ukrainian education ecosystem showed informal aspects of self-organization, which contributed to stabilization not only at the individual but also at the level of group development [13]. The process of socio-psychological regulation at the individual and social can manifest itself by maintaining a certain rhythm of development, a certain level of well-being and tolerance to uncertainty. Factors contributing to the preservation of a certain level of resilience and well-being include an increase in psychological volunteering, and a critical approach to history, social events and communal dialogue [14].

To one of the forms of stabilization we include a certain pedagogical interaction with students in universities within non-formal education programs. For example, formal training at the University of Educational Management (Ukraine) during the first active phase of the war was delivered as a so-called "live psychological laboratory". It was complemented by innovative forms of training: daily streaming counseling classes, elements of SALT – system of accelerated learning and teaching, Accelerated Learning (AL) and Intensive Learning (IL) [15, 16], weekly support group to help students in their daily activities, supervision certified course of eco-centered facilitation; International discussion club PsyDetox). This approach made it possible to achieve good academic results, it contributed to the assimilation of not only the curriculum but help stabilize the psychological condition of students and teachers during the war adversity [13]. This provides a certain ground to assume that the spontaneous tendency of any even formal system to stabilize itself in critical situations can be related to a form social therapy.

3. Experimental research on the development of psychological sustainability: a rationale

To this form of a social psychotherapy, we include ecofacilitative training of psychologists which is antithetical to the existing system of traditional directive teaching. The main differences between eco-facilitative education and traditional education are: short-term vs long term teaching exposure, personal orientation vs program or curriculum orientated process, tolerance for ambiguity vs intolerance for ambiguity. Experimental social therapy pedagogy is also hybrid, facilitates individual educational and teaching trajectories of the student and the teacher.

This form was implemented at the time of experimental distance learning called "The Intensive Course of Eco-Centered Facilitation" (ICEF-course). ICEF-course is focused on achieving the following educational outcomes: appropriation of eco-centered facilitation theoretical background; introduction into a non-deficiency principal of post-traumatic growth and development; acquisition of non-directive guidance of group dynamics in uncertainty and semantic chaos; development of eco-facilitative counselling skills as well as the skills for professional deliberative practice, assessment of the psychologist's competence.

The intensive character of the pedagogical course was ensured by its multi-factor determination: the personal interest of students, the demonstration of live eco-facilitative (psychological) sessions with real clients and professional assistance, implementation of individual educational trajectories, combination of mandatory and optional components of the course. A special focus of the course is the therapeutic effect for students in the conditions of the war adversity and forced emigration.

The course program is designed for 72 academic hours over two months (classes 2 days a week) and includes three main modules: live Eco-facilitative counselling sessions, their analysis held by P. V. Lushyn; methodological rationale for ecofacilitative counselling and practice; Eco-facilitative internship: gaining the experience of a client, a counselor, a supervisor. The course program covers the following topics: psychological and social conditions of the personality change process; principal features of the personality change process; psychology of self-development and self-organization of personality; theoretical, methodological, and empirical analysis of scientific research on personality change process; ecofacilitation and the principle of ecology; ecosystem in the personality change process; psychological guidance of post-traumatic development; practice of ecofacilitation in the conditions of the modern world. Autonomous student's work included: deliberative practice, recording eco-facilitative sessions, writing reflective essays. Optional: participation in the work of PsyDetox International Discussion Club and supervisional group sessions. The learning process involves minimal regulation in terms of its intensity and evaluation of the results of each participant. It is focused on toleration of uncertainty, creating conditions for the manifestation of one's own educational motivation, the possibilities of designing and implementing an individual learning trajectory and psychological stabilization in terms of development.

The research goal is to study the socio-therapeutic potential of ecofacilitative pedagogy as an important factor for social and individual stabilization (by means of preparation of future professionals) in wartime adversity in Ukraine.

4. Methodology

Indicators of psychological stabilization in terms of changes during experimental training are studied by means of content analysis of the reflective essays, current and final written reviews of students. These indicators are semantically represented as psychological emergent, shifts in emotional (sensations, feelings, interest, interest, insight, catharsis), cognitive (comprehension, understanding, cognition), behavioral (attitudes, actions, experience, skills), value (meanings, worldview) spheres. Content analysis allows to determine the psychological state, identify attitudes, interests, intentions, values, belief systems, "models of the world", focuses of attention of the authors of the texts and is characterized by objectivity of conclusions, rigor of the procedure. It consists in the choice of semantic units of the analysis, a quantification of the text (similar to the standard methods of classification by selected groups) with the subsequent interpretation of the results. Semantic units or units of the analysis could be the concepts, simple sentences or judgments, topics which are expressed in whole semantic paragraphs, parts of texts, events, etc. The units of the account can be estimated by the frequency of mention in texts or the physical length of the texts, the area of the text is filled with semantic units, the number of lines, paragraphs, signs of the text, etc. [17–19].

In this paper, the content analysis included: a) the definition of a universal category that answers the most generalized question of content analysis – indicators of psychological stabilization of the individual in terms of change and development; b) formulation of the basic judgment (statement) "Studying at the ICEF-course contributes to the psychological stabilization of the individual in terms of development"; c) decomposition of complex sentences into simple ones with the transformation of adjective and participle turns into separate simple sentences; d) identifying and counting all semantic units of analysis of simple sentences that fall under the basic judgment and represent a complete thought. The selection of analytical units in the texts was carried out by two experts, the results were compared and subsequently analyzed.

As factors of stabilization in terms of personal change and development are considered: age, professional and previous educational experience, activity and experience of psychological assistance acquired during the course. Professional experience reflects the professional status of the subject either as a practicing psychologist, or as a student – a future psychologist, or as a representative of other professional groups. Previous educational experience is an indicator that combines the presence of basic psychological education and specialization in different modalities of psychological assistance (absent, polymodal, monomodal); level (number of hours) of specialization in "Ecofacilitation" modality (initial, intermediate, advanced), as well as membership in the public association of psychologists (Ukrainian Association of Environmental Psychological Assistance). Indicators of academic activity, motivation and success are studied according to the following markers: the intensity of attendance at the main and optional events of the course, internship in the course – the experience gained by the client, consultant and supervisor, as well as the results and scope of deliberative practice (independent work on recording consultations).

The participants of the study were students of the ICEF-course ($N = 51$), the average age 32 ± 5.3 years, men 11.8 %, women 88.2%. Among them are those who study Psychology at the university 13.7 %, psychologists of organizations and self-employed psychologists 29.4 %, workers in other fields (economic, legal, IT, military, artistic) 34 % and temporarily unemployed 22.9 %. Outside of Ukraine 39.2 %. The sample is not homogeneous, randomized, everyone could take part in the course. Statistical processing includes descriptives, frequency, cluster analysis, Kruskal-Wallis Test and carried out using the SPSS statistical package.

5. Results and discussions

An example of semantic units of text analysis, which are indicators of stabilization in terms of change and development, are judgments that testify to the dynamics at different levels: emotional – "There are many insights that I will analyze later", "This work inspired me so much", "Difficult situations in me can be viewed as opportunities I never thought before"; cognitive – "It became aware that I know what I want", "I saw order and began to trust myself", "I found another cycle in my life – 8 months", "I realized my main mistake"; behavioral – "Previous time I failed, now I will succeed, will pass through it calmly", "Now with new powers and new strengths I will move further", "And after the second Sunday at night I felt the strength and inspiration to answer her"; value-semantic – "New meanings are being born for the future life", "I strongly pushed my interpretation of children", "Now I have received avoidant experiences and cooperation with the invisible", "This course has become useful for me not only in professional growth, but also in personal growth". The total number of selected judgments is 2777. The analytical units allocated from them are 441 (100 %), including: emotional nature – 147 (33.3 %), cognitive-rational – 109 (24.8 %), behavioral – 129 (29.2 %), semantic – 56 (12.7 %).

Clustering of variables made it possible to distinguish four groups of participants in which the parameters under study are manifested differently (table 1).

In different groups according to the studied parameters, statistically significant differences or differences at the level of trends were identified. The indication of the features of the manifestation of psychological stabilization of the individual and professional, educational experience, educational activity of participants in the context of different typological groups is presented (figure 1).

On the basis of the results, we obtained a typology of development and stabilization of the personality in the conditions of intensive training.

Type 1 – "professionals" (23.5 %), who active in learning and stable in development. By age, it is probably the oldest group of people with significant professional psychological experience, good educational experience and specialization in an eco-facilitative approach. They always attend

Table 1. Manifestation of the studied parameters in typological groups.

Researched parameters	Type 1	Type 2	Type 3	Type 4	Sig.
Age	29.0	25.2	20.8	30.1	0.089
Professional psychological experience	30.3	24.8	26.7	21.9	0.153
Previous educational experience	31.6	24.8	16.8	32.3	0.045
Main activity	33.3	23.3	36.0	9.5	0.000
Optional activity	32.7	29.4	28.1	4.5	0.000
Practicing on the course	44.5	15.5	31.8	18.6	0.000
Deliberative practice	31.5	16.5	44.9	19.2	0.000
Indicators of stabilization	27.3	23.0	39.6	14.9	0.003

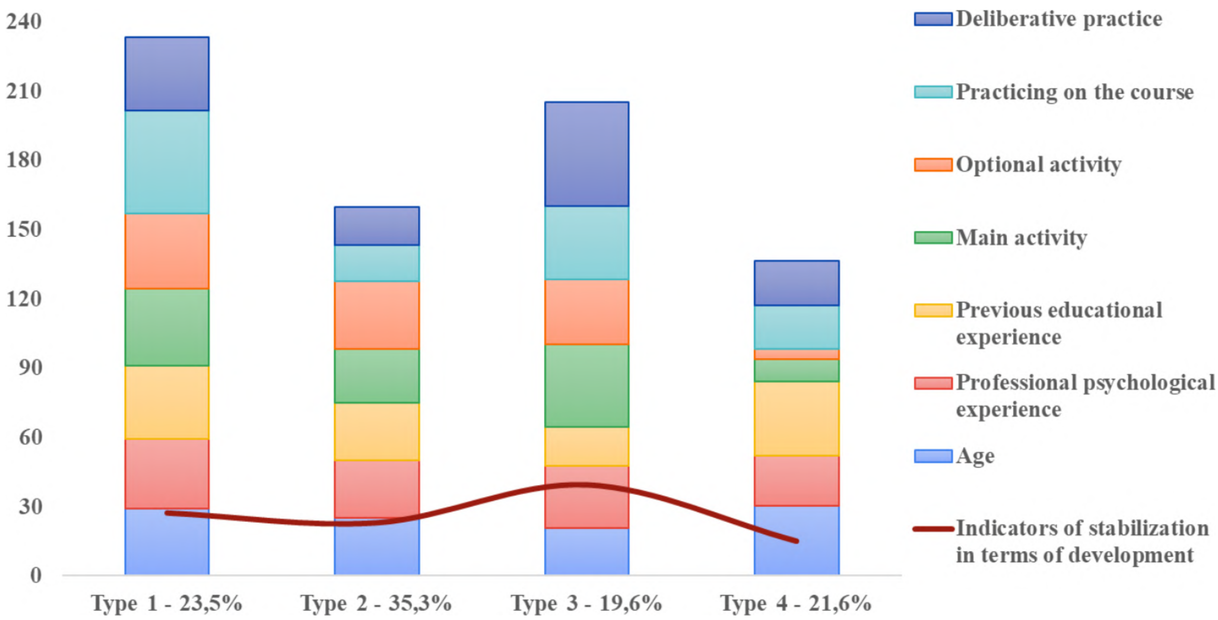

Figure 1. Psychological development of personality in different typological groups.

the sessions in the main and optional classes of the course, are motivated and actively practice during classes, are interested and gain the experience of a client, counselor, supervisor. Although they their weakest spot is not making use the opportunities of the deliberate practice to the fullest. Therefore, in this aspect their zone of professional development is not significant So, their key features are a convincing educational and professional psychological background; they have the highest activity in all components of the course program, with the exception of deliberative practice. The students of the group are stable in terms of psychological dynamics – emotional, cognitive, behavioral; value reactions and changes. In this type, the highest educational activity is manifested on the "wave" of the stable personal and psychological development.

Type 2 "those who are interested – interesants" (35.3 %) – actively observing, although refraining from active practice, they demonstrate moderate, evolutionary development. These participants are the most distant from professional psychological activities, but at the same time they are quite knowledgeable and have a moderate level of specialization in the eco-facilitative approach. They are involved in the optional activities of the course as much as possible. Not too active in main classes, and obtaining the experience of the client, a counseling and supervising. Their personal and psychological development is associated with psychological changes of an evolutionary nature.

Type 3 "beginners" (19.6 %) are persistent in learning, mastering eco-facilitation, very dynamic in their personal development. These are the youngest participants in age, close to professional psychological activity, since among them there is a significant proportion of applicants for psychological education, but now they have minimal experience and initial specialization in the eco-facilitative approach. They are characterized by maximum inclusion in the main classes of the course and somewhat lower in electives. Gaining client's experience and moderate, rather, "cautious" practice in the classroom as counselors and supervisors, they actively complement their own deliberative practice. Against the background of such a motivated attitude towards learning, the psychosemantic markers of their psychological dynamics look the most expressive and convincing.

Type 4 "observers" advanced and beginners (21.6 %). They support their psychological balance. Among them are both professional psychologists and representatives of other professions. There are those who have maximum learning experience, specialization in the eco-facilitative approach and are members of the community of eco-facilitators. There are others amongst them who are just beginning their acquaintance with psychology and the ecofacilitative approach. But all of them are united by the fact that they are not very active in the learning process, they mainly participate in the basic training sessions that provide an opportunity to observe and discuss "live psychological case". They are not active in practicing during classes, independent work, logging. In terms of personal and psychological, their dynamics is minimal. Regarding this type, the question arises – what is the meaning of learning for them? The answer may be that passive observation, being in an ecological educational context, and therapeutic space allows the most knowledgeable and ignorant of psychology, to find and maintain their own psychological balance in the eco-therapeutic educational format.

6. Conclusion

The results obtained allow us to formulate the following conclusions. First, the hypothesis is confirmed that the experimental educational and therapeutic format of accelerated preparation of future processionals, psychologist in particular, in the context of non-formal education. This form of education can be attributed to social therapy, which creates conditions for the implementation of various strategies for the personal growth and development of students.

Secondly, age, professional psychological experience may influence the dynamics of psychological stabilization. Most convincing factors are the educational experience of psychological specialization, staying in the educational and therapeutic environment and the possibility of performing various types of educational activities within the existing intrinsic motives and developmental trajectories.

Thirdly, the strategies of learning and psychological stabilization in terms of development and change are manifested nonlinearly and are represented by dynamically changing types of "observer", "actively interested","persistent student", "professional". These types reflect some trends in a wide range of unique strategies for personality stabilization and development – from passive observation to active practice with oneself and others at different stages of the professional and life pathways.

Fourthly, staying in a developing educational and psychological environment constitutes the antithesis for exposure to the military environment which opens up a certain prospect for psychological well-being, resilience of an individual, and therefore of society.

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References

[1] Racioppi F, Rutter H, Nitzan D, Borojevic A, Carr Z, Grygaski T J, Jarosińska D, Netanyahu S, Schmoll O, Stuetzle K, Akker A V D and Kluge H H P 2022 *The Lancet* **400**(10356) 871–873 URL `https://doi.org/10.1016/S0140-6736(22)01739-1`

[2] Lubrani O "The war has caused the fastest and largest displacement of people in Europe since World War II" URL `https://ukraine.un.org/en/175836-war-has-caused-fastest-and-largest-displacement-people-europe-world-war-ii`

[3] Zaliska O, Oleshchuk O, Forman R and Mossialos E 2022 *The Lancet* **399**(10334) 1450–1452 URL `https://doi.org/10.1016/S0140-6736(22)00615-8`

[4] Haque U, Naeem A, Wang S, Espinoza J, Holovanova I, Gutor T, Bazyka D, Galindo R, Sharma S, Kaidashev I P, Chumachenko D, Linnikov S, Annan E, Lubinda J, Korol N, Bazyka K, Zhyvotovska L, Zimenkovsky A and Nguyen U S D T 2022 *BMJ Global Health* **7**(9) e009550 URL `https://doi.org/10.1136/bmjgh-2022-009550`

[5] Slone M and Mann S 2016 *Child Psychiatry & Human Development* **47**(6) 950–965 ISSN 1573-3327 URL `https://doi.org/10.1007/s10578-016-0626-7`

[6] Su Z, McDonnell D, Cheshmehzangi A, Bentley B L, Ahmad J, Šegalo S, da Veiga C P and Xiang Y T 2023 *Perspectives on Psychological Science* **18**(4) 908–911 URL `https://doi.org/10.1177/17456916221109609`

[7] Hrushetskyi A 2022 Self-assessment of happiness by the population of Ukraine: results of a telephone survey conducted on September 7-13, 2022 URL `https://www.kiis.com.ua/?lang=eng&cat=reports&id=1145&page=1`

[8] Goodwin R, Hamama-Raz Y, Leshem E and Ben-Ezra M 2023 *International Journal of Disaster Risk Reduction* **85** 103487 ISSN 2212-4209 URL `https://doi.org/10.1016/j.ijdrr.2022.103487`

[9] Karamushka L M, Kredentser O V, Tereshchenko K V, Delton Y, Arefniya S V and Paskevska I A 2022 *Wiadomości Lekarskie* **LXXV**(8 Part 1) 1854–1860 URL `https://doi.org/10.36740/WLek202208107`

[10] Ungar M, Theron L, Murphy K and Jefferies P 2021 *Frontiers in Psychology* **11** ISSN 1664-1078 URL `https://doi.org/10.3389/fpsyg.2020.607994`

[11] Lushyn P and Sukhenko Y 2021 *East European Journal of Psycholinguistics* **8**(1) URL `https://doi.org/10.29038/eejpl.2021.8.1.lus`

[12] Lushyn P V and Sukhenko Y V 2022 *IOP Conference Series: Earth and Environmental Science* **1049**(1) 012080 URL `https://doi.org/10.1088/1755-1315/1049/1/012080`

[13] Lushyn P and Sukhenko Y 2022 Pidgotovka majbutnih psyhologiv na pochatku vijny v Ukrai'ni: format zhyvoi' psyhologichnoi' laboratorii' (Training of future psychologists at the beginning of the war in Ukraine: the format of a living psychological laboratory) *Psyhologo-pedagogichnyj suprovid profesijnoi' pidgotovky ta pidvyshhennja kvalifikacii' fahivciv v umovah vojennogo stanu* ed Brjuhoveckaja A and Hyl'ko S (Kyiv: Universytet menedzhmentu osvity) pp 14–18

[14] Korostelina K V 2020 *Peace and Conflict Studies* **27**(2) 4 URL `https://doi.org/10.46743/1082-7307/2020.1689`

[15] Serdyukov P 2008 *Journal of Research in Innovative Teaching* **1**(1) 35–39 URL `https://www.researchgate.net/publication/268516488`

[16] Imel S 2002 Accelerated Learning in Adult Education and Training and Development Trends and Issues Alert 33 ERIC Clearinghouse on Adult, Career, and Vocational Education Columbus, OH URL `https://eric.ed.gov/?id=ED462551`

[17] Kostenko N and Ivanov V 2003 *Experience of content analysis: models and practices [Experience of content analysis: models and practices]* (Kyiv: Centr vil'noi' presy)

[18] Spinks N 2014 Quantitative Content Analysis URL `https://tinyurl.com/mthv8a9c`

[19] Schreier M 2012 *Qualitative Content Analysis in Practice* (SAGE Publications Ltd.)

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Development of the hydrological regime of the Uzh River under backwater conditions to minimize the urban environment risks

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Development of the hydrological regime of the Uzh River under backwater conditions to minimize the urban environment risks

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Abstract. The impact of high dams with large reservoirs with long-term regulation is covered in the scientific literature quite widely. The information and recommendations on the use of low-head dam for the creation of the low backwater are not enough. Large dams reduce the mean annual flow downstream, the magnitude and frequency of floods, lead to the accumulation of suspended solids, nutrients compounds (nitrogen, potassium, phosphorus), which, together with increasing temperature leads to the "blooming" phenomenon of the reservoir and the overgrowth, create barrier for sediments transferring and fish. The main reason of the deterioration of the water quality is the water retention time in the formed reservoir and anthropogenic pollution, although the literature rarely provides quantitative data of the water retention time for the evaluated reservoir. The environment risks assessment of the impact of the reservoir should include the calculation of the water retention time, the presence of pollutants in the river, which may indicate future negative effects. The hydrological regime of the river after the backwater creation should correspond to the natural flow with the floods passage by the entire width of the river bed, which will significantly improve flood management, sediments transport and washing the river bed. The significant risk is the shallowing of the river downstream, the amount of water discharged into the downstream should be at least 75% of the river flow. Releasing the flow to the downstream with an overflow or through fish passage structures allows to enrich the water with oxygen. In order to preserve biodiversity, it is necessary to create or leave islands and shallow water areas for the needs of waterfowl. To ensure an environmentally friendly regime operation of the low-head dam the crest of the spillway structure should be at the bottom level along the entire cross section. The low-head dam should be provided with automatic control system and communication with the hydrometric station for a quick response to the flow changes in the river.

1. Introduction

In recent decades, more and more attention has been paid to the impact of artificial hydraulic structures on the river environment and the minimization of risks. Considerable attention is paid to water replenishment of floodplain [1,2]. The problem of disconnection between the floodplain and the river takes plays as a result of the flood control dykes' construction in the urbanized areas, and the water replenishment problem of the floodplain and oxbow lakes is possible to solve by the river flow management and artificial structures. The article [3] analyses the prospects of watering the old river bed and the oxbow lake in the urbanized area, which is protected from floods by earth dykes. It is not possible to restore the connection between the floodplain and the river by destroying dykes on the urbanized areas. The old river bed is completely dry and the oxbow lake is silted and overgrowth because of the absence of the connection between the river and the floodplain in the summer. The analysis of the hydrological regime of the river and various replenishment scenarios showed that it is necessary to create backwater in order to water replenish the old river bed and increase the volume of the oxbow lake.

The large dam construction experience and the analysis of their operation indicates their significant impact on the hydrological regime of the river and the floodplain. High dams primarily affect the hydrological regime of rivers: decrease the mean annual flow downstream especially in the dry season, and decrease the magnitude and frequency of floods [4].

The large dams change the chemical parameters of water quality. Kamidis et al [5], Fantin-Cruz et al [6] indicate the significant decrease in suspended solids due to sedimentation in the reservoir, nitrogen concentration due to denitrification, decrease in phosphorus concentration in the water downstream and anaerobic conditions in the lower layers of the reservoir. Deep reservoirs are characterized by temperature stratification and the temperature increase in the summer due to long retention time. In the article [7] is indicated that large reservoirs in highly urbanized watersheds can improve the water quality downstream reducing the turbidity and concentrations of pollutants due to storage in reservoir. Shallow water reservoirs with the long water retention time accumulate nutrients (phosphorus, nitrogen), which, together with the warming of the water in the summer, leads to the water “blooming” which leads to decrease the oxygen in the water, and phytoplankton transporting into downstream [8]. The water quality and temperature changing, nutrients and sediments storage are associated with long water retention time in large reservoirs, high dams also cause disconnect habitat along the river [9], decrease in flood flow, and as a result limit floodplain replenishment.

The researches of low-head dam are paid less attention. The study of five small reservoirs with storage capacity of 0.14–0.64 hm^3 in the Nerbioi-Ibaizabal watershed showed that the lack of ecological flow in the summer negatively affects the density, richness and diversity of macroinvertebrates in the areas below the dam [10]. Ignatius and Rasmussen [11] note the increase in temperature, the decrease in the concentration of nitrates and phosphates, and the dissolved oxygen increase in the water downstream when water overflow the crest of the dam. In the article [12] is noted that the impact of low-head dams depends on the composition of sediments, the length of the reservoir and the construction of the dam, which can retain sediments or allow them to be transported downstream.

At the same time, studies of the impact of dams built by beavers [13, 14] also indicate the water speed decrease in the reservoir, fine sediment storage, the temperature increase, the dissolved oxygen decrease, the increase in the dissolved organic carbon and ammonium transport downstream, the decrease suspended solids and nitrates transport downstream. That changes lead to the complication of existence and as the result increase of biodiversity.

One of the important factors affecting the formation of the regime of dissolved and suspended substances, biogenic elements in water and bottom sediments, the conditions of life of aquatic organisms, their populations and groups is the water retention time, which shows the time that water or any dissolved substance remains in the reservoir. The water exchange is formed due to the water inflow from the catchment area and its outflow from the reservoir, contributing to the intensive passage of chemical and biological processes. According to Oksiyuk et al [15], the water retention time should not exceed 7–9 days for the optimal development of phytoplankton and reducing the probability of water ”blooming”. The optimal functioning of the hydrobionts is ensured if water retention time is rates to 4–6 days. The zoobenthic microorganisms change to the less valuable pelophilic species if the reservoir water retention time ranged from 5 to 11 days. In reservoirs with long water retention time more than 15–20 days, the accumulation of organic substances and biogenic substances can be observed, which leads to oxygen deficiency and “flowering” of water [6].

The reason for the overgrowth of water bodies with higher aquatic vegetation is the high biogenic substances concentration (nitrogen, potassium, phosphorus) and the low water depth. Nowak and Lawniczak-Malińska [16] showed that reeds can grow in the large amplitude of lake depth, but its optimal growth is observed in the range from 0 to 1.6 m, while the roots reach the maximum depth of 1.7 m. At the same time, less overgrown water bodies are characterized by the depth of more than 2.5 m with the low nitrogen and potassium concentrations [17].

The aquatic ecosystem sustainability is also affected by the amount of water discharged downstream. Many authors confirm the need to ensure the natural regime of the ecological flow: variability, magnitude, frequency, duration, timing and rate of change, which should be from 75% to 100% of the river flow [9,18,19]. Waligórski and Janicka [8], Ignatius and Rasmussen [11] emphasize the importance of water overflow downstream, which create additional water aeration downstream.

The anthropogenically altered water environment requires the assessment of many factors that may negatively affect the environment in the urbanized areas. Urban river demande integrated water resources management even for environmental improvement projects. Relevance of the topic: floodplain water replenishment aimed to improve the urbanized environment requires intervention in the hydrological regime of the river bed, which requires a comprehensive assessment and development of hydrological regime means of minimizing the environment risks.

The aim of the work is to assess the main parameters that undergo changes during the backwater creation and to develop an environmentally friendly hydrological regime operation of the low-head dam to minimize the environment impacts.

2. Materials and methods

2.1. Study area

The natural flow of the Uzh River in the central part of the city is characterized by significant irregularity and frequent floods. The most catastrophic floods occur in the cold period of the year, there are low water levels with periodic rain floods in the summer. The floodplain of the Uzh River is limited by flood protection dyke in the central part of the city. It is necessary to create the backwater near the area of Bozdos Park in the central part of the city to water replenishment of the floodplain lake and old river bed.

To replenish the old riverbed, it is planned to install the flap gates at the entrance to the old riverbed and at the end to create the required depth of up to 2.0 m. Water replenishment of the floodplain lake is carried out through the tubular spillway. To provide water exchange in the lake, it is connected to the old riverbed by tubular spillway. The backwater on the Uzh River is planned to be created by two flap gates to minimize main riverbed narrowing. The small reservoir is formed as the result of the backwater with the height of approximately 2.5 m (figure 1). The fish passage is provided for free fish movement. The backwater creation for water replenishment is necessary during the dry season. Since there is the spawning period from March 25 to May 15 which prohibit the activities that may affect fish spawning in the Transcarpathian region, it is actually possible to start to create backwater after the May 16th.

2.2. Study methods

The seven cross-sections were analysed to establish the hydrological regime of the river in the area of the future reservoir, which located at the distance of 250 m, the first at the flap gates cross-section and the seventh at the top of the reservoir. The curves of the $h = f(Q)$ were calculated for each cross-section on the base of the curve for Uzhhorod hydrologic station and the water levels were calculated in the natural riverbed for typical years of the stable summer-autumn low flow of the 95%, 75% and 50% probability. The function of the average velocities and river flow in the cross-sections were determined.

Figure 1. Study area: 1 – flap gates; 2 – back water; 3 – pipes for water replenishment; 4 – floodplain lake; 5 – old river bed; 6 – spillway for old river bed replenishment.

The simulation of the backwater creation and water level fluctuations in the formed reservoir including the water replenishment of the floodplain lake and old riverbed was carried out by the water balance method according to the equation:

$$\Delta W = W_{inf} + Pf - E_0 f - W_{out} - RI_{lake} - RI_{orb} - SI, \tag{1}$$

where ΔW – change in storage, m^3; W_{inf} – inflow volume, m^3; P – precipitation, m; f – reservoir area, m^2; E_0 – evaporation from the water surface in the ice-free period, m; W_{out} – volume of the ecological flow downstream, m^3; RI_{lake} – volume of the flow into the floodplain lake, m^3; RI_{orb} – volume of the flow into the old riverbed, m^3; SI – seepage outflow from river, m^3.

Meteorological data (temperature, wind speed, precipitation) for the specified years are taken from the data of the Uzhhorod climate station. The riverbed is the lowest points for the groundwater discharge in the area from the backwater beginning to the territory of the Bozdos Park. The water rising will cause temporary soil wetting losses in the aeration zone, but compared to permanent seepage into the Bozdos Park area, these losses can be neglected. Bozdos Park is located in the middle of the river loop, and the ground flow in the middle loop has the direction from upstream side of the dam to the downstream of the river loop. These seepage losses were calculated according to equation (4) of the article [3] as the seepage losses from the river with backwater to the river downstream. The methodology for determining precipitation, evaporation from the water surface as components of the water balance is described in work [3].

The length of the backwater in the Uzh River is calculated according to the equation:

$$L = k\frac{H}{i}, \tag{2}$$

where L – length of the backwater, m; k – coefficient for mountain rivers is 1.2; H – hydraulic head, m; i – hydraulic gradient of the river.

The hydraulic retention time calculated as relation between reservoir volume and mean river inflow during the period of back water formation by equation [20]:

$$HR = \frac{V}{Q_{mean}} 86400, \tag{3}$$

where HR – hydraulic retention time, day; V – reservoir volume obtained from the curve of water levels and volumes, m^3; Q_{mean} – mean river inflow during the period of backwater formation, m^3/s; 86400 – coefficient to covert seconds into day.

To regulate the water flow in the river, the flap gates were chosen, which allow in horizontal position to pass sediments without creating barrier during the flood. The lifting of the flap gates to create backwater begins with flow increasing in the river after May 15th (136 calendar day). The ecological flow to the downstream is at least 75% of the flow entering the reservoir. At the same time, the floodplain lake and the old riverbed are being filled, which is possible due to the spring flood period. To maintain the water retention time at the range of 4-6 days in the old riverbed and the floodplain lake, the optimal water supply to the old riverbed is 0.5 m^3/s, to the lake is 0.3 m^3/s. The simulation carried out for two scenarios of the reservoir operation in the interaction of Uzh River – floodplain lake – old riverbed: maintenance of the constant maximum water level of the backwater (scenario 1); using the flow accumulated in the reservoir to increase the ecological flow up to 75% to the downstream (scenario 2).

3. Results and discussion

The environmental impact of the dam on the hydrological, biological, geomorphological parameters of the reservoir and water quality can be summarized using the diagram (figure 2). At the same time, the hydrotechnical structures for water replenishment of the floodplain is not the permanent backwater like the ordinary dam. The backwater is temporarily formed by the flap gate after the end of spawning (after the May, 15) and is maintained until the end of October (before autumn floods). The ordinary dam creates the physical barrier for the fish movement. The fish passage is necessary to move cross the dam.

The main impact on the river is the creation of the backwater for the certain water volume accumulation, which create due to the reduction of water discharge to the downstream. The impact of the low-head dam with small reservoir volume on flood flow and flood levels is insignificant, and the risk can be minimized due to the gates design. The evaporation from water surface increase, but this loss is appreciable for big water surface and shallow reservoir. The water level increase due to the backwater increases the groundwater table in the hyporheic zone, which also leads to river flow loss. But at the same time, the recharge of groundwater can have both the negative (increasing ground water table) and the positive is the water replenishment to maintain the biodiversity of the floodplain during the dry season. Water level fluctuation could cause groundwater changes and lowering the soils bearing capacity and as a result banks instability and foundations subsidence on the urban area.

The water speed decreases in the reservoir, which leads to the sedimentation of suspended solids, pollutants, nutrients and the deposition of bottom sediments. The creation of non-flowing conditions in the presence of significant nutrients concentrations can lead to the overgrowth of the reservoir and, to its “blooming” under the condition of rising temperatures. The rapid development of algae leads to the decrease of the oxygen concentration in water and as a result the fish death. The pollutants and nutrients accumulation are directly related to the water retention time in the reservoir, and as shown by Oksiyuk et al [15], the water retention time in the range of 4-6 days provides optimal conditions for the biodiversity. It is possible to ensure short water retention time only by minimizing losses from the reservoir and regular ecological flow to the downstream, which should replicate the natural hydrological regime of the river.

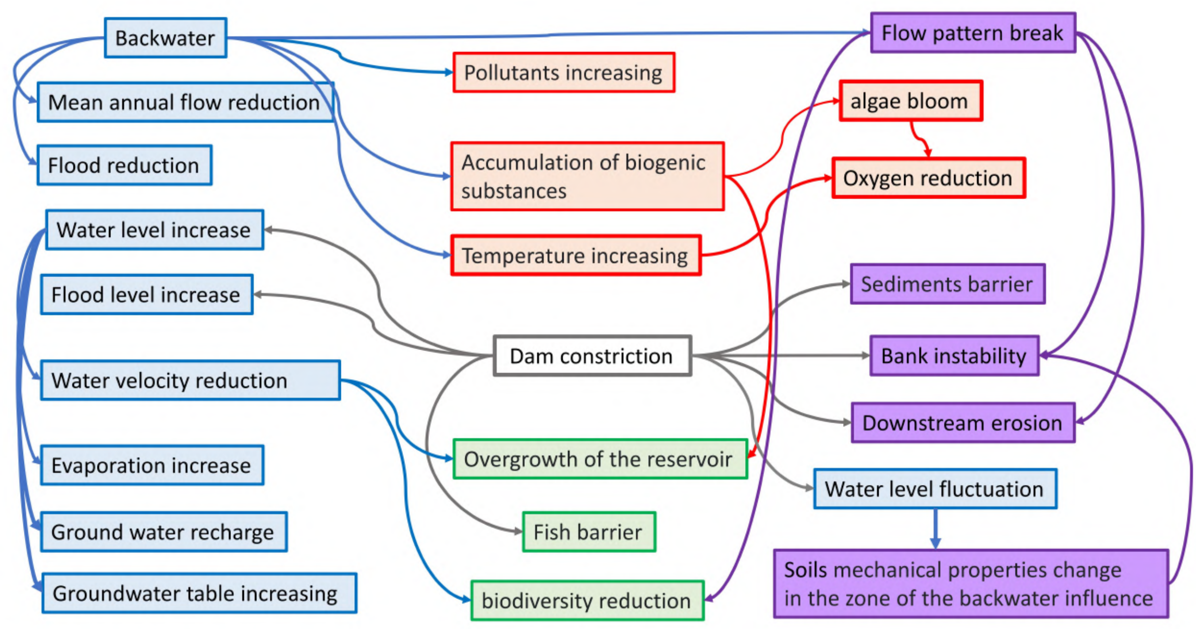

Figure 2. Environmental risks of the reservoir creating on the river: blue – hydrological and hydraulic; red – water quality; green – biological; violet – geomorphological.

Sediment transport occurs mostly during the floods, therefore, to ensure the transport of sediments, it is necessary to ensure the free passage of flood discharges across the full width of the riverbed. Since the water replenishment of the floodplain should be carried out during the dry season, there is no need to create backwater in the period from November to May. So, the main floods will pass through the full cross section of the river, which will ensure the sediments transportation and washing of the riverbed. On the example of the Uzh river, the highest floods occur in March in the year of 95% probability; in March and April in the mean year; in January, February and March for the year of 75% probability. During these periods, backwater is not created and nothing prevents the sediments movement. The flap gate is completely going down when the flow exceeds 103.8 m^3/s, which allows sediment to pass through the gate sections and ensures periodic washing out of the reservoir.

Ensuring the intensity of water exchange, which is formed due to inflow into the reservoir, has the greatest impact on water quality and reservoir overgrowth. Preservation of the shallow water part on the islands formed by sediments will preserve the biodiversity of wetland birds of the Uzh River. The reservoir volume without bottom clearing and preservation of the sediments side as shallow water for coastal fauna is 319,680 m^3, the water retention time of the reservoir on the Uzh River is 0.44 days for the year of 95% and 0.3 days for the mean year and the year of the 75%, which can be considered sufficiently intensive and favourable for the biodiversity. The water retention time is 6.3 days for floodplain lake, and one is 1.5 days in the old riverbed, which is also quite favourable intensity.

The simulation showed that ensuring the short water retention time in the floodplain lake and the old riverbed while maintaining the constant maximum water level in the Uzh river at the level of 110.2 m leads to the reduction of the ecological flow to the downstream (red line on the figure 3, figure 4 and figure 5) by 40% of the inflow for the very dry year of the 95% and the year of 75% probability, which is associated with long-term low flows in the summer period. If ecological flow is supported at the level of 75% of the inflow (black line on the figure 3, figure 4 and figure 5), it is possible to use the accumulated during the rain floods water in the reservoir, that will decrease the water level in the reservoir (blue line on the figure 3, figure 4 and figure 5) due to losses on evaporation, filtration and discharges into the floodplain lake and old riverbed. For some summer days with low water flows, it will be necessary to close the gates and stop the fresh water supply to the old riverbed (green line on the figure 3), which will not significantly affect the water quality in the old riverbed due to the short water retention time, but the water level will slightly decrease.

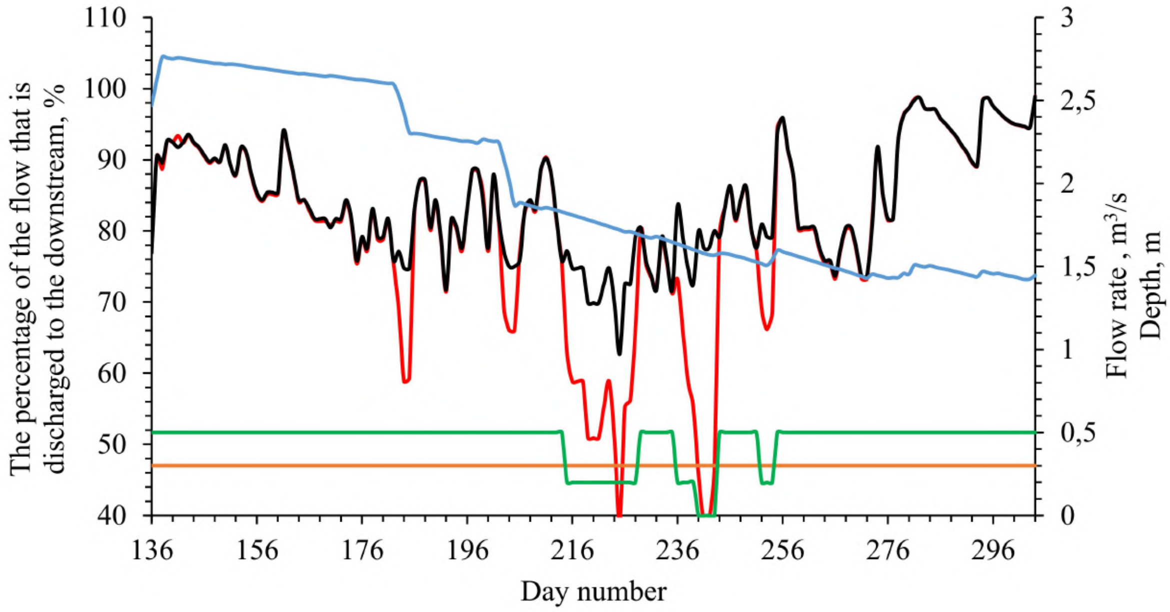

Figure 3. Simulation of the hydrological regime of the Uzh River under backwater conditions during very dry year of the 95% probability: red line – the percentage of the flow (ecological flow) that is discharged to the downstream (scenario 1); black – ecological flow to the downstream that is higher than 75% of the inflow (scenario 2); green – water supply to the old riverbed; orange – water supply to the floodplain lake; blue – the water level in the reservoir on the Uzh River (scenario 2).

The constant water level in the reservoir makes it easy to realize in practice the uniform water supply into the floodplain the dry season. The use of the second scenario with water level fluctuation in the reservoir makes it difficult to regulate the flow into the lake and the old riverbed, and will require complex automation and manoeuvring by the gates at the entrance to the old river and the lake, otherwise the water supply into the lake and old riverbed will be decrease due to head decrease.

4. Conclusions

The general requirements for creating the hydrologically friendly river regime in urbanized areas:

- the water retention time in the range of 4-6 days to avoid future environmental risks;
- the depth of the reservoir should be more the 2.0m with shallow areas;
- the hydrological regime of the river should be corresponded to the natural with ecological flow at least 75% of the inflow of the river;
- the crest of spillway structure should be designed on the bottom level along the entire cross section to provide sediments transporting and decrease flood risk;

- automatic control system and communication with the hydrometric station should be installed for a quick response to the flow changes in the river.

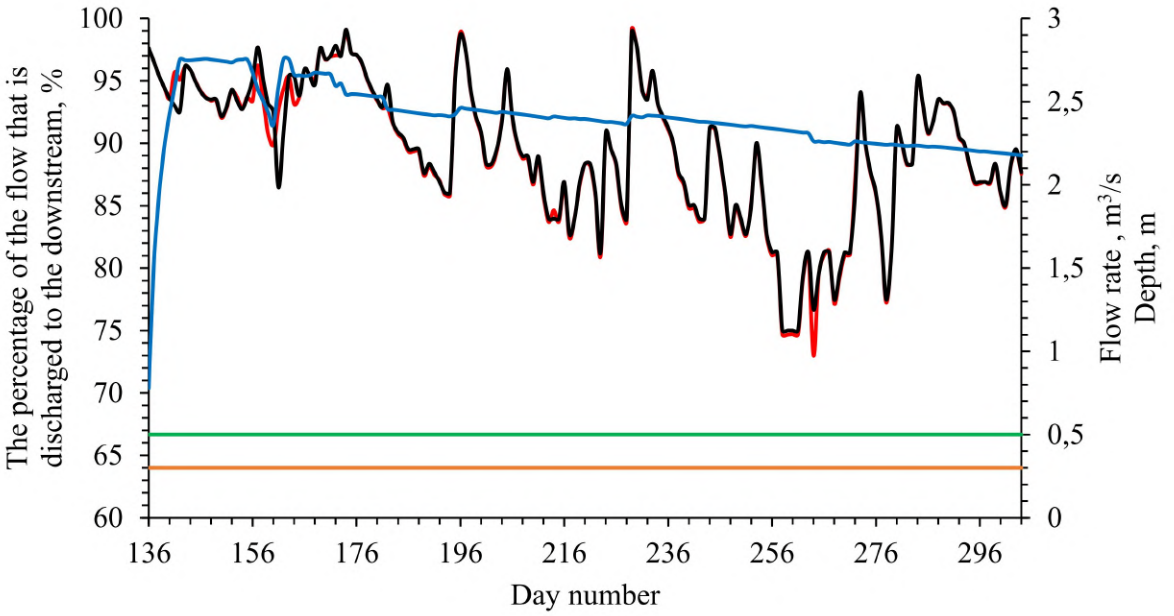

Figure 4. Simulation of the hydrological regime of the Uzh River under backwater conditions during the mean year of the 50% probability: notations are the same as on the figure 3.

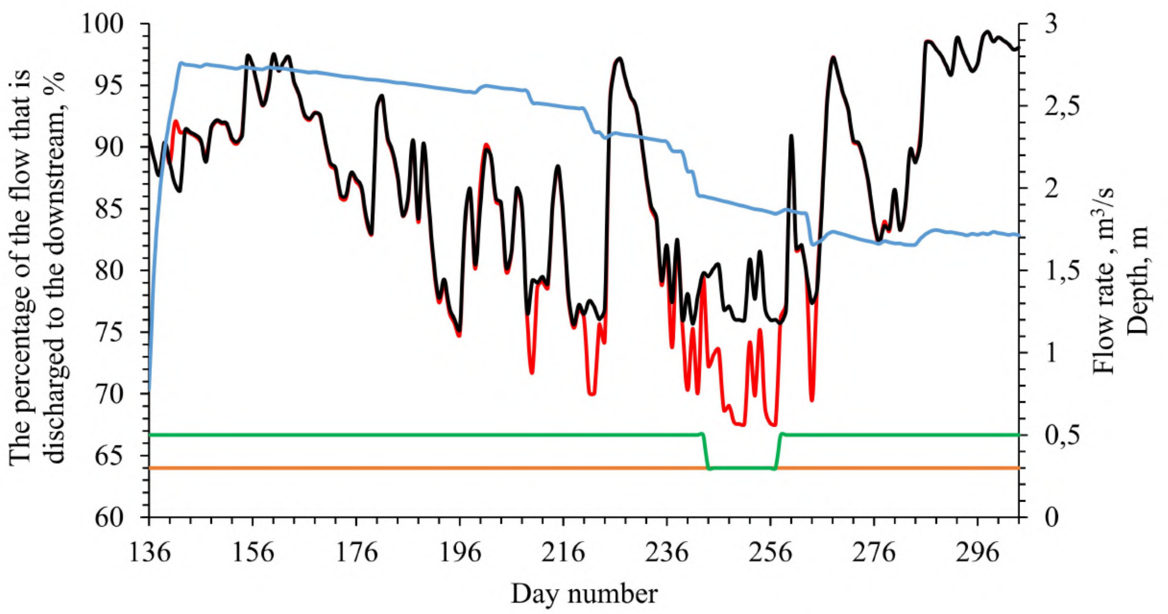

Figure 5. Simulation of the hydrological regime of the Uzh River under backwater conditions during the year of the 75% probability: notations are the same as on the figure 3.

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References

[1] Liu J, Zhang Q, Wang Z, Yang B and Li Y 2022 *Water and Environment Journal* **36**(1) 105–114 URL https://doi.org/10.1111/wej.12742

[2] Lóczy D and Dezső J 2019 Landscape Rehabilitation: The Old Drava Programme *The Drava River: Environmental Problems and Solutions* ed Lóczy D (Cham: Springer International Publishing) pp 367–391 ISBN 978-3-319-92816-6 URL https://doi.org/10.1007/978-3-319-92816-6_21

[3] Velychko S and Dupliak O 2021 *Ecological Engineering & Environmental Technology* **22**(4) 30–38 ISSN 2719-7050 URL https://doi.org/10.12912/27197050/137871

[4] Villablanca L, Batalla R J, Piqué G and Iroumé A 2022 *Journal of Hydrology: Regional Studies* **41** 101060 ISSN 2214-5818 URL https://doi.org/10.1016/j.ejrh.2022.101060

[5] Kamidis N, Koutrakis E, Sapounidis A and Sylaios G 2021 *Water* **13**(20) 2832 ISSN 2073-4441 URL https://doi.org/10.3390/w13202832

[6] Fantin-Cruz I, Pedrollo O, Girard P, Zeilhofer P and Hamilton S K 2016 *Hydrobiologia* **768**(1) 223–238 ISSN 1573-5117 URL https://doi.org/10.1007/s10750-015-2550-4

[7] Shahady T D and Cleary W C 2021 *Journal of Environmental Management* **297** 113334 ISSN 0301-4797 URL https://doi.org/10.1016/j.jenvman.2021.113334

[8] Waligórski B and Janicka E 2021 *Rocznik Ochrona Środowiska* **23** 151–167 URL https://doi.org/10.54740/ros.2021.010

[9] Ai X S, Sandoval-Solis S, Dahlke H E and Lane B A 2015 *River Research and Applications* **31**(2) 181–192 URL https://doi.org/10.1002/rra.2728

[10] Martínez A, Larrañaga A, Basaguren A, Pérez J, Mendoza-Lera C and Pozo J 2013 *Hydrobiologia* **711**(1) 31–42 ISSN 1573-5117 URL https://doi.org/10.1007/s10750-013-1459-z

[11] Ignatius A R and Rasmussen T C 2016 *Journal of Hydrology: Regional Studies* **8** 145–161 ISSN 2214-5818 URL https://www.sciencedirect.com/science/article/pii/S2214581816300519

[12] Csiki S and Rhoads B L 2010 *Progress in Physical Geography: Earth and Environment* **34**(6) 755–780 URL https://doi.org/10.1177/0309133310369435

[13] Ecke F, Levanoni O, Audet J, Carlson P, Eklöf K, Hartman G, McKie B, Ledesma J, Segersten J, Truchy A and Futter M 2017 *Environmental Research Letters* **12**(11) 113002 URL https://doi.org/10.1088/1748-9326/aa8979

[14] Larsen A, Larsen J R and Lane S N 2021 *Earth-Science Reviews* **218** 103623 ISSN 0012-8252 URL https://doi.org/10.1016/j.earscirev.2021.103623

[15] Oksiyuk O P, Polyschuk V S, Zhuravleva L A *et al.* 1991 *Hydrobiological Journal* (6) 3–10

[16] Nowak B and Lawniczak-Malińska A E 2019 *Water* **11**(12) 2651 ISSN 2073-4441 URL https://doi.org/10.3390/w11122651

[17] Lawniczak-Malińska A E and Achtenberg K 2018 *Water* **10** 498 ISSN 2073-4441 URL https://doi.org/10.3390/w10040498

[18] Monico V, Solera A, Bergillos R J, Paredes-Arquiola J and Andreu J 2022 *Science of The Total Environment* **810** 151630 ISSN 0048-9697 URL https://doi.org/10.1016/j.scitotenv.2021.151630

[19] Velychko S and Dupliak O 2021 Estimation of the Ecological Flow of Mountain River in Ukrainian Carpathians for Small Hydropower Projects *Proceedings of EcoComfort 2020* ed Blikharskyy Z (Cham: Springer International Publishing) pp 490–498 ISBN 978-3-030-57340-9 URL https://doi.org/10.1007/978-3-030-57340-9_60

[20] Fantin-Cruz I, Pedrollo O, Bonecker C C and Zeilhofer P 2015 *Hydrological Sciences Journal* **60**(9) 1508–1519 URL https://doi.org/10.1080/02626667.2014.933224

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Improvement technology of water regulation and methods of calculating the parameters of modular drainage systems on the lands of the humid zone

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Improvement technology of water regulation and methods of calculating the parameters of modular drainage systems on the lands of the humid zone

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Abstract. The article examines water regulation on drained lands by innovative modular drainage systems with multi-level connection of regulating drains, diagrams of their design parameters are given. The main goal of the article is to demonstrate the results of analytical studies of water regulation by drainage modules under the condition of laying drains at different depths are given. The equations derived in this article allow you to use them to calculate the distance between regulating drains of different installation depths, perfect in terms of the degree and nature of the opening of the aquifer during infiltration water supply within drainage modules. Variants of the application of methods for calculating the parameters of regulatory drainage modules are proposed, which allow predicting groundwater level regimes, establishing watershed lines between perfect shallow-deep drains.

1. Introduction

Most of the drainage systems operated in Ukraine were built more than 30 years ago. On many of them, the drainage does not work as necessary, and therefore the optimal water regime is not observed. This is due to the physical wear and tear of the elements of the drainage system or violation of the rules of operation of the drainage system or a change in the direction of agricultural use of the drained lands themselves. Another possible reason is the low quality of construction [1, 2]. Therefore, for the successful use of territories with constructed but defective drainage, it is often necessary to carry out restoration works, which will ensure the optimal water regime of the soil, and, accordingly, agricultural production at the required level. However, approaches to design have changed, new, in certain cases, more effective designs of drainage systems have appeared. Climate change must also be taken into account. So, the current state of water management systems in the humid zone requires new effective approaches to both construction and reconstruction [1–4], as well as to the design of regulatory drainage networks [5].

In order to effectively regulate the water regime of the soil, we have proposed new innovative designs of closed regulatory drainage networks, which include drainage modules from periodically repeated drains with different laying depths (figure 1).

Conducted experimental studies show that regulatory networks, which include drainage modules, have a greater hydrological effect than their counterparts and allow to unload the upper layers of the soil from excess infiltration water in a faster time, which is especially important

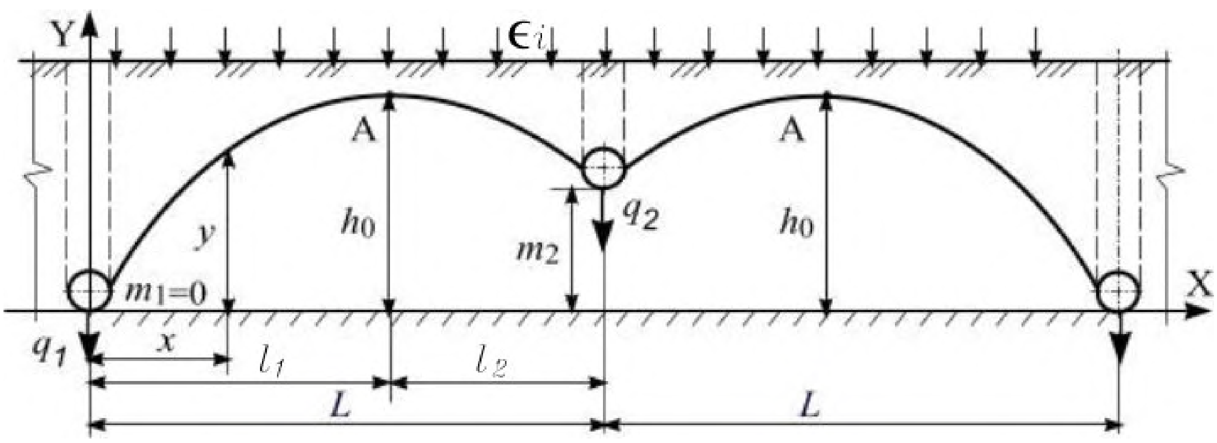

Figure 1. Scheme for calculating groundwater levels between shallow and deep drains during infiltration feeding (the deep drain is located on the waterproof layer, the shallow one is above the waterproof layer), the A-point of the water separation between shallow and deep drains.

during critical periods of the operation of drainage networks (the period of spring floods and the period of summer torrential rains).

Equally important for regulating the water regime of the soil is the calculation of the parameters of the adopted drainage schemes.

2. Materials and methods

If the drainage network is reinforced with additional drains, then in this connection Oleynyk [6,7] proposes a method of filtration calculation of drainage for irrigation arrays. Approximate calculations of such drainage are based on the method of filtration resistances [6]. In the case of imperfect drains by the degree of opening of the aquifer (the drains are above the waterproof layer) and imperfect drains by the nature of the opening of the aquifer (the drains are protected by filtering material), a linear equation is used to predict and calculate the position of groundwater levels when constructing the technique of filtration resistances in any intersection of the filtration flow.

3. Results and discussion

We will calculate the parameters of the regulating drainage module during infiltration water supply of perfect drains of shallow and deep laying (shallow laying drain – perfect according to the degree and nature of the opening of the aquifer, deep – perfect according to the nature of the opening of the aquifer).

Consider the steady, uniform movement of the filtration flow of water in the directions of the deep and shallow drains (from point A, figure 1) of the regulating drainage module in homogeneous soil.

The calculation of the mode groundwater level (for the circuit in figure 1) can be performed on the basis of the Boussinesq's equation, which includes partial derivatives

$$k_f \frac{\partial}{\partial x}\left(h\frac{\partial h}{\partial x}\right) + \varepsilon_i = 0, \tag{1}$$

where ε_i – vertical infiltration of water, k_f – soil filtration coefficient. Since $h = h(x)$, the equation (1) includes ordinary derivatives and will be written in the form

$$k_f \frac{\mathrm{d}}{\mathrm{d}x}\left(h\frac{\mathrm{d}h}{\mathrm{d}x}\right) + \varepsilon_i = 0. \tag{2}$$

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Dividing the variables of equation (2), we find

$$d\left(h\frac{\mathrm{d}h}{\mathrm{d}x}\right) = -\frac{\varepsilon_i}{k_f}\mathrm{d}x, \tag{3}$$

and after integration we get

$$h\frac{\mathrm{d}h}{\mathrm{d}x} = -\frac{\varepsilon_i}{k_f}x + C_1; \tag{4}$$

$$h^2 = -\frac{\varepsilon_i}{k_f}x^2 + 2C_1 \cdot x + 2C_2; \tag{5}$$

In the case of water infiltration, when $\varepsilon_i > 0$, we obtained equation (5) – the equation of an ellipse.

Let's determine the constants C_1 and C_2 separately for a deep drain arranged on a water-resistant layer and a shallow hanging drain imperfect in degree and perfect in nature of the opening of the aquifer.

Since when $x = 0, h = 0$ and when $x = l_1, h = h_0$, then from equation (5) we find

$$C_2 = 0; h_0^2 = -\frac{\varepsilon_i}{k_f}l_1^2 + 2C_1 \cdot l_1 + 2C_2. \tag{6}$$

where

$$C_1 = \frac{1}{2l_1}\left(h_0^2 + \frac{\varepsilon_i}{k_f}l_1^2\right). \tag{7}$$

Substituting the values of the constants C_1 and C_2 into the equation (5), we get

$$h_0^2 = -\frac{\varepsilon_i}{k_f}x^2 + \frac{1}{l_1}\left(h_0^2 + \frac{\varepsilon_i}{k_f}l_1^2\right)x. \tag{8}$$

After simple transformations in accordance with (figure 1), we make sure that equation (8) defines an ellipse centered on the axis $0x$ at the point x

$$\frac{h_0^2}{\frac{1}{4}\frac{k_f}{\varepsilon_i l_1^2}\left(h_0^2 + \frac{\varepsilon_i}{k_f}l_1^2\right)^2} + \frac{\left[x - \frac{1}{2}\frac{k_f}{\varepsilon_i \cdot l_1}\left(h_0^2 + \frac{\varepsilon_i}{k_f}l_1^2\right)\right]^2}{\frac{1}{4}\left[\frac{k_f}{\varepsilon_i l_1}\left(h_0^2 + \frac{\varepsilon_i}{k_f}l_1^2\right)\right]^2} = 1. \tag{9}$$

So,

$$x = \frac{1}{2}\frac{k_f}{\varepsilon_i l_1}\left(h_0^2 + \frac{\varepsilon_i}{k_f}l_1^2\right)^2 = \frac{1}{2}\left(l_1 + \frac{k_f h_0^2}{\varepsilon_i l_1}\right), \tag{10}$$

where x is the abscissa of the point of the largest h_0 value for a deep drain.

Assuming in equation (10) that $x = l_1$, we find $2l_1 = l_1 + \frac{k_f}{\varepsilon_i}\frac{h_0^2}{l_1}$, where

$$l_1 = h_0\sqrt{\frac{k_f}{\varepsilon_i}}. \tag{11}$$

For an imperfect shallow drain when $x = l_1, h = h_0 - m_2$, and when $x = l_1 + l_2, h = m_2$, then from equation (4) we find

$$(h_0 - m_2)^2 = -\frac{\varepsilon_i}{k_f}l_1^2 + 2C_1 l_2 + 2C_2; \tag{12}$$

$$m_2^2 = -\frac{\varepsilon_i}{k_f}(l_1 + l_2)^2 + 2C_1(l_1 + l_2) + 2C_2. \tag{13}$$

where

$$m_2^2 - (h_0 - m_2)^2 = -\frac{\varepsilon_i}{k_f}(l_1 + l_2)^2 + \frac{\varepsilon_i}{k_f} l_1^2 + 2C_1 l_2; \tag{14}$$

$$2C_1 = \frac{1}{l_2}\left[\left(2h_0 m_2 - h_0^2\right) + \frac{\varepsilon_i}{k_f}\left(2l_1 l_2 + l_2^2\right)\right]; \tag{15}$$

$$2C_2 = (h_0 - m_2)^2 + \frac{\varepsilon_i}{k_f} l_1^2 - \frac{l_1}{l_2}\left[\left(2h_0 m_2 - h_0^2\right) + \frac{\varepsilon_i}{k_f}\left(2l_1 l_2 + l_2^2\right)\right]; \tag{16}$$

Substituting the determined values of the constants into the equation (17), we obtain

$$\begin{gathered}\tfrac{k_f}{\varepsilon} h^2 + \left\{x - \left[\left(h_0 m_2 - \tfrac{1}{2}h_0^2\right)\tfrac{k_f}{\varepsilon l_2} + \left(l_1 + \tfrac{1}{2}l_2\right)\right]\right\}^2 = \\ = \frac{k_f m_2^2}{2\varepsilon_i} + \frac{1}{2}l_2^2 + \frac{k_f}{2\varepsilon_i}\left(h_0 - m_2\right)^2 + \frac{h_0^2}{4}\left[\left(2m_2 - h_0\right)\frac{k_f}{\varepsilon_i l_2}\right]^2;\end{gathered} \tag{17}$$

$$A^2 = \frac{k_f m_2^2}{2\varepsilon_i} + \frac{1}{2}l_2^2 + \frac{k_f}{2\varepsilon_i}\left(h_0 - m_2\right)^2 + \frac{h_0^2}{4}\left[\left(2m_2 - h_0\right)\frac{k_f}{\varepsilon_i l_2}\right]^2. \tag{18}$$

The equation (18) is the equation of an ellipse.

$$\frac{h^2}{A^2 \frac{\varepsilon_i}{k_f}} + \frac{\left\{x - \left[\left(h_0 m_2 - \tfrac{1}{2}h_0^2\right)\tfrac{k_f}{\varepsilon l_2} + \left(l_1 + \tfrac{1}{2}l_2\right)\right]\right\}^2}{A^2} = 1 \tag{19}$$

The abscissa x is the point of the largest h_0 value for a shallow drain

$$x = \frac{\frac{k_f}{\varepsilon_i}\left(h_0 - m_2\right)^2 - \left(2h_0 m_2 - h_0^2\right)\frac{k_f}{\varepsilon_i}\frac{l_1}{l_2} - \left(l_1^2 + l_1 l_2\right)}{\frac{k_f}{\varepsilon_i l_1} h_0^2 - (l_1 + l_2) + h_0\left(\frac{h_0 k_f}{l_2\varepsilon_i - 2m_2}\right)}, \tag{20}$$

$$h_0 = A\sqrt{\frac{\varepsilon_i}{k_f}}. \tag{21}$$

Taking into account the value of A, we get

$$h_0^2 \frac{k_f}{\varepsilon_i} = \frac{k_f m_2^2}{2\varepsilon_i} + \frac{1}{2}l_2^2 + \frac{k_f}{2\varepsilon_i}\left(h_0 - m_2\right) + \frac{h_0^2}{4}\left[\left(2m_2 - h_0\right)\frac{k_f}{\varepsilon_i l_2}\right]^2, \tag{22}$$

where

$$l_2^2 - \frac{h_0^2}{2}\left[\left(h_0 - 2m_2\right)\frac{k_f}{\varepsilon_i}\right]^2 \cdot \frac{1}{l_2^2} + \frac{k_f}{\varepsilon_i}\left[m_2 + \left(h_0 - m_2\right)^2 - 2h_0^2\right] = 0; \tag{23}$$

or

$$l_2^4 - \frac{k_f}{\varepsilon_i}\left[h_0^2 + 2m_2\left(h_0 - m_2\right)\right] l_2^2 - \frac{h_0^2}{2}\left[\left(h_0 - 2m_2\right)\frac{k_f}{\varepsilon_i}\right]^2 = 0. \tag{24}$$

After solving the biquadratic equation (23), we get

$$l_2 = \left\{\frac{1}{2}\frac{k_f}{\varepsilon_i}\left[h_0^2 + 2m_2 h\right] \pm \sqrt{\frac{k_f^2}{4\varepsilon_i^2}\left[h_0^2 + 2m_2\left(hy_0 - m_2\right)\right]^2 + \frac{h_0^2}{2}\left[\left(h_0 - 2m_2\right)\frac{k_f}{\varepsilon_i}\right]^2}\right\}^{\frac{1}{2}}. \tag{25}$$

Then the total distance (figure 1) between the drains of shallow and deep laying $L = l_1 + l_2$.

If in (25) in the root expression $\frac{h_0^2}{2}\left[(h_0 - 2m_2)\frac{k_f}{\varepsilon_i}\right]^2$, and $h_0 = 2t_2$, then $l_2 = 0$ (if there is a sign before the root (–) and if we take a sign before the root (+)), then

$$l_2 = \sqrt{\frac{k_f}{\varepsilon_i}\left[h_0^2 + 2m_2\left(h_0 - m_2\right)\right]}. \tag{26}$$

The total distance (figure 1) between the drains of shallow and deep laying L

$$L = l_1 + l_2 = h_0\sqrt{\frac{k_f}{\varepsilon_i}} + \sqrt{\frac{k_f}{\varepsilon_i}\left[h_0^2 + 2m_2\left(h_0 - m_2\right)\right]}. \tag{27}$$

The largest value of $h = h_0$ (figure 1) can be determined

$$h_0 = \frac{1}{2}\sqrt{\frac{\varepsilon_i}{k_f}} + \left(\frac{k_f}{\varepsilon_i}\frac{m_2^2}{L} + L\right) \tag{28}$$

at the point with the abscissa $x = \frac{1}{2}\left(\frac{k_f}{\varepsilon_i}\frac{m_2^2}{L} + L\right)$.

The value of the ordinate $h(x)$ at an arbitrary value x can be determined using (28).

$$h(x) = \sqrt{\left(\frac{m_2^2}{L} + \frac{\varepsilon_i}{k_f}L\right)x - \frac{\varepsilon_i}{k_f}x^2}. \tag{29}$$

The resulting equations (13), (27) were studied for the possibility of using them to calculate the distance L between perfect regulating drains of shallow-deep laying according to the degree and nature of the opening of the aquifer during infiltration water supply. Equations (13), (27) and (29) include rather relative, interdependent values of l_1, l_2 and h_0.

Analyzing the equation (29), it can be argued that it has an advantage over (8) because it includes only two given values – the distance between the drains L and the hanging height m_2 of an imperfect drain of shallow laying above the waterproof layer.

Thus, the given methods of calculating the parameters of regulating drainage modules operating in the mode of intensive reduction of groundwater level during infiltration water supply in the case of established groundwater filtration allow to predict groundwater level regimes and calculate the distances between drains of shallow-deep laying perfect in terms of the degree and character of the opening of the aquifer.

4. Conclusions

- According to the results of theoretical and experimental research, generally accepted methods and mathematical models describing the movement of water in the soil have been improved.
- Calculations of the parameters of the drainage modules make it possible to predict the groundwater level regimes between perfect and imperfect (material) drains of shallow-deep laying, as well as to obtain the position of the groundwater level in dynamics and in the time during which the groundwater level decrease from the surface of the earth to a depth equal to the drainage rate.
- The methods obtained theoretically and experimentally should be used to calculate the distances between perfect and imperfect (material) drains of shallow and deep laying according to the degree and nature of the opening of the aquifer during infiltration water supply.

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References
[1] Kovalenko P I, Chalyy B I and Tyshchenko A I 1991 *Reconstruction of ameliorative systems* (Kyiv: Urozhay)
[2] Klimov S V and Klimova A V 2022 *IOP Conference Series: Earth and Environmental Science* **1049**(1) 012038 ISSN 1755-1315 URL https://doi.org/10.1088/1755-1315/1049/1/012038
[3] Gurklys V and Kvaraciejus A 2013 *Žemės ūkio mokslai* **20**(3) 170–178 ISSN 2424-4120 URL https://doi.org/10.6001/zemesukiomokslai.v20i3.2740
[4] Fedchenko V 2003 *Substantiation of modernization and reconstruction of reclamation systems in the humid zone on the basis of ecological and reclamation monitoring data* Ph.D. thesis Institute of Water Problems and Land Reclamation of NAAS Kyiv, Ukraine 06.01.02
[5] Martynov S, Fylypchuk V, Zoshchuk V, Kunytskyi S, Safonyk A and Pinchuk O 2018 *Journal of Water and Land Development* 93–99 ISSN 1429-7426, 2083-4535 URL https://bibliotekanauki.pl/articles/292733
[6] Oleynyk A Y 1981 *Geohydrodynamics of drainage* (Naukova dumka)
[7] Polyakov V L 1997 *Hydraulics and hydromechanics* **58** 78–84

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Quantitative assessment of water quality in the Vidsichne reservoir (Zhytomyr, Ukraine)

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Quantitative assessment of water quality in the Vidsichne reservoir (Zhytomyr, Ukraine)

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Abstract. The modern approach to the implementation of water management activities is based on a quantitative assessment of the quality of water resources, which includes a certain set of indicators to reflect the needs of users in the composition and properties of water, to assess their condition, etc. Ecological assessment is a preliminary stage and a condition for ecological standardization of surface water quality. To analyze the compliance of water quality with ecological standards, the obtained results are compared with the values of ecological standards for the corresponding water body. The study carried out a quantitative assessment of water quality in the Vidsichne reservoir, near Zhytomyr (Ukraine). This assessment is based on the introduction of risk weighting factors from certain types of pollutants to the calculation formula of the integral indicator. Monitoring studies on hydrochemical indicators in the reservoir showed an increase in manganese content to 0.40 mg/dm^3. To calculate the integral indicator of water quality, manganese and the related level of oxygen dissolved in water, biological oxygen consumption (BOC) were selected. It was established that the water in the reservoir belongs to the fourth quality class, that is, it is polluted. A model map of manganese concentration was built and the ecological coefficient of water quality was calculated, which indicates a 5-fold excess of ecological standards. The use of a graphic method of comprehensive assessment of the state of water in any reservoir is substantiated. The increase in manganese content is due to the seasonal increase in air temperature. The constructed mathematical model of the dependence of manganese content on temperature makes it possible to predict the state of the water body depending on climatic conditions and indicates an increase in the value of this indicator from 12°C and above. Quantitative assessment of water quality in the reservoir based on the sum of ecological indicators reflects the needs of users in the composition and properties of water and makes it possible to assess their condition.

1. Introduction

Pollution of water bodies is one of the components of the global environmental problem, which is getting bigger every year. Many changes that occur in the chemical composition of water in rivers are caused by climatic changes. The available numerous methods and techniques are directly or indirectly based on the transformation of quantitative indicators into qualitative indices of the ecological state. According to the analysis of numerous studies, the objective assessment of the ecological state of water bodies is based on the combined use of hydrochemical and hydrobiological data [1–3]. As part of the standard approach, the indicators determined at individual points of the water body are compared with the normative values of the corresponding indicators [4–6]. However, recently, an alternative method of water quality assessment, which uses biotesting, has become widespread [7].

Over the past few years, there has been increasing concern about the decline in the quality and availability of drinking water. This decline in water quality is mostly due to anthropogenic practices such as agriculture, industry, domestic and municipal waste. In order to minimize the recorded impact on water bodies, it is extremely important to understand the overall composition, structure and dynamics of these ecosystems, which allows the implementation of measures (example, more specific procedures, public information and monitoring programs) to ensure the protection of water resources and ensure water quality [8, 9].

Water supplied to the city of Zhytomyr centrally from the city water supply is taken from the Teteriv River in the area of the Vidsichne water intake. Water in the reservoir is characterized by unstable quality, especially during the spring flood and summer months. Water quality during these periods deteriorates, according to the level of phytoplankton, manganese and other indicators.

In previous years, illegal sand mining was carried out near the reservoir, which increased the amount of silt in the reservoir and, accordingly, the accumulation of manganese compounds in the reservoir. Natural processes, such as rock erosion, climatic conditions affect the composition of soil and water in the reservoir area. This leads to a change in the chemical composition of water and affects the development of the reservoir ecosystem [10].

According to the Water Framework Directive 2000/60/EC (WFD), the ecological status of a water body is based on specific physical, chemical, biological and hydromorphological parameters. Especially for highly altered water bodies, the parameters are determined according to the type of reservoir [6].

The purpose of the study was to establish and substantiate the quality of water in the Vidsichne reservoir, near Zhytomyr, using a comprehensive assessment based on the introduction of weighted risk factors from certain types of pollutants to the calculation formula of the integral indicator. The selected pollutant was manganese and the associated level of oxygen dissolved in water, biological oxygen consumption (BOC).

2. Research methods and tools

Three methods were used to quantitatively assess water quality in the Vidsichne reservoir [11,12]. This is the determination of the modified *water pollution index, the ecological coefficient of water quality graphically and the level of the quality of a water object* based on a three-level classification by characteristics. The research used a method of assessing water quality based on the water pollution index, which is common in practice.

The definition of the *water pollution index* is based on indicators of the chemical composition of water, which makes it possible to use information from surface water monitoring. The calculation was based on the following ingredients: manganese, BOC, oxygen dissolved in water. These indicators were chosen because they are mandatory for surface water calculations. According to the methodology, the average arithmetic value was calculated for each indicator, which was compared with their maximum permissible concentrations for each indicator. The water pollution index (WPI) was calculated according to the formula:

$$WPI = \frac{1}{n} \sum_{i} \frac{C_i}{MPC_i}, \tag{1}$$

where C_i is the average concentration of one of the n indicators of water quality, mg/dm^3; MPC$_i$ is the maximum permissible concentration of one of the n indicators of water quality, mg/dm^3; n is the number of indicators [11].

The *ecological coefficient of water quality* in the reservoir was determined according to the standard method with the construction of a map model in the form of a circular diagram with radii scales [12]. The value of division is the MPC of the indicator, and each axis corresponds to the year of observation of this indicator. After constructing the diagram, the ecological coefficient of water (K_e) quality is determined according to the formula:

$$K_e = \frac{F_{fact}}{F_{optim}}, \tag{2}$$

where F_{fact} is the area of the diagram limited by the actual values of the hydrochemical characteristics; F_{optim} is the area of the diagram, limited by the optimal (normative) values, which is found according to the formula:

$$F_{optim} = \pi r^2, \tag{3}$$

where r is the radius of the circle, which is limited by optimal (normative) values.

The third *technique relates to establishing the level of water quality* of the water object Vidsichne. For this purpose, a three-level classification was carried out: 1) according to the signs of recurrence of pollution cases; 2) multiples of exceeding standards; 3) creation of general evaluation scores.

The first degree of classification is based on the determination of the level of pollution resistance. As a measure of the persistence of pollution, the value of recurrence of cases of exceeding the MPC (H), which is common in hydrochemical practice, was used, which was found according to the formula:

$$H = \frac{N_{MPC}}{n}, \tag{4}$$

where H is the frequency of cases of exceeding the MPC of the ingredient; N_{MPC} stands for the number of analysis results in which the content of the ingredient exceeds its maximum permissible concentration; n is the total number of analysis results for the ingredient.

After conducting an analysis of contamination based on repeatability, the following characteristics were identified as qualitatively different:

- pollution can be observed in individual samples, that is, it can be single;
- pollution may be unstable;
- pollution may not be dominant, but obviously persistent;
- pollution can be dominant, i.e. characteristic.

Qualitative expressions of selected characteristics of water pollution were awarded quantitative expressions in points (table 1).

Table 1. Water classification of water bodies according to the signs of recurrence of pollution cases.

Frequency, %	Characteristics of water pollution of water bodies based on recurrence	Partial evaluation points expressed conditionally	Partial evaluation points absolute values
[0;10]	single	a	1
[10;30]	unstable	b	2
[30;50]	stable	c	3
[50;100]	characteristic	d	4

The second level of classification is based on establishing the level of pollution, the measure of which is the indicator F of the multiplicity of exceeding the MPC:

$$F = \frac{C}{C_{MPC}}, \tag{5}$$

where, F is the frequency of exceeding the MPC for the ingredient; C is the concentration of the ingredient in the water of the water body, mg/dm^3; C_{MPC} is the maximum permissible concentration of the ingredient, mg/dm^3.

According to the analysis of water pollution of water bodies, four qualitatively different degrees of pollution level were separated according to the frequency of exceeding standards by a separate pollutant: 1) low; 2) average; 3) tall; 4) very high. Qualitative expressions of the selected characteristics were assigned quantitative expressions of gradations in points (table 2).

When combining the first and second stages of water classification for each of the considered ingredients, generalized estimates of water quality are obtained for a certain period of time (table 3). Generalized characteristics are assigned generalized evaluation points S, obtained as a summary of individual characteristics, as an example, table 3 [11].

Informational materials of the State Agency of Water Resources and the State Department of Environmental Protection in the Zhytomyr region served as the initial data for the calculation of environmental indicators and the construction of models. The data of hydrochemical observations of the laboratory of the city water supply were used as the initial information

Table 2. Water classification of watercourses according to the level of pollution.

Multiplicity of exceeding standards	Characteristics of the pollution level	Partial evaluation points expressed conditionally	Partial evaluation points absolute values
[0;2]	low	a_1	1
[2;10]	average	b_2	2
[10;50]	high	c_3	3
[50;100]	very tall	d_4	4

Table 3. Variations in the water quality of watercourses are possible depending on individual ingredients and pollution indicators.

Comprehensive characteristics of the state of water pollution of the watercourse	Characteristics of the water quality of the watercourse	Partial evaluation points expressed conditionally	Partial evaluation points absolute values
Low-level single pollution	slightly polluted	$a \cdot a_1$	1
Single contamination of medium level	polluted	$a \cdot b_1$	2
High-level single contamination	dirty	$a \cdot c_1$	3
Single pollution of a very high level	dirty	$a \cdot d_1$	4
Unstable low-level pollution	polluted	$b \cdot a_1$	2
Unstable pollution of medium level	dirty	$b \cdot b_1$	4
Unstable pollution of a high level	very dirty	$b \cdot c_1$	6
...	...	...	...

for the study of the qualitative condition of the Vidsichne reservoir, namely, the indicators of manganese, BOC and the content of dissolved oxygen in the water.

3. Results and discussions

Water supplied to consumers in the city of Zhytomyr is taken from the Teteriv River in the area of the Vidsichne reservoir, which is located at a distance of about 8 km from the city (figure 1). A certain supply of water accumulates in the reservoir with very little water exchange, which is due to a geographical position and climatic conditions: firstly, insignificant precipitation, and secondly, long-term hot weather in the summer during the last three years. In addition, due to the incorrect operation of dredgers in Vidsichne, the current moved to the opposite bank. A stagnant zone has formed near the water intake, where silt accumulates. This is an environmental problem that needs a separate solution. Water from streams flowing out of swamps enters the reservoir and contains an increased chemical content of metal ions (for example, iron). Sewage pollution of settlements upstream of the reservoir is observed.

Figure 1. Map of the location of the Vidsichne reservoir.

The specified reasons in the conditions of regulation of the Teteriv River led to a sharp deterioration in the quality of water in the Vidsichne water intake. If during the design period of the city's water supply facilities, the quality of water in the Teteriv River met the requirements for the first class of surface water supply sources by all indicators, but at the present time, due to a number of ingredients, such compliance no longer exists. The analysis of hydrochemical and hydrobiological indicators presented by the chemical laboratory of the city water supply showed that the level of phytoplankton (blue-green algae) and zooplankton in the river water has increased dramatically in recent years. The accumulation of a significant amount of organic nutrients also causes a persistently elevated level of microbiological indicators in the summer-autumn period in comparison with previous years. Such a physical indicator as turbidity increased to an average monthly level of 11.7 mg/dm^3 and a maximum of 14.9 mg/dm^3

during 2020. In addition, prolonged hot weather in the summer period in recent years led to a significant decrease in the content of dissolved oxygen and an increase in carbon dioxide.

As a result of the long-term increase in water temperature in the Vidsichne reservoir, the death of blue-green algae begins, which leads to the deterioration of water quality, and the content of manganese, which reaches 0.40 mg/dm^3, increases. Therefore, according to the Water Framework Directive 2000/60/EC (WFD), the ecological status of a specific water body is assessed by both comprehensive and specific indicators. Such a characteristic indicator for the Vidsichne reservoir is the concentration of manganese ions [6].

Manganese belongs to microelements that significantly affect the metabolic processes in the body of plants and animals. It is one of the main elements necessary for water oxidation in the processes of photosynthesis and carbon utilization in carbo-oxidation reactions around green algae. In aquatic ecosystems, manganese in concentrations exceeding the maximum permissible level becomes biologically dangerous and can be considered as a toxicant. The main factors that increase the manganese content in water are temperature and hydrobiological indicators, that is, the amount of phytoplankton.

The research used the results of chemical analyses of water quality indicators in the reservoir, which were carried out during 2019–2021. To calculate the water pollution index by formula (1), indicators related to the biological oxygen consumption (total), dissolved oxygen, and manganese were used (table 4).

Table 4. The results of the calculation of water pollution indices for the Vidsichne reservoir.

Indicator	C/MPC, ratio for O_2 norm/C in 2019	C/MPC, ratio for O_2 norm/C in 2020	C/MPC, ratio for O_2 norm/C in 2021
BOC$_{full}$	1.650	1.636	1.770
Dissolved oxygen	0.666	0.595	0.617
Manganese	8.000	6.200	8.000
The sum of ratios	10.316	8.428	10.387
Water pollution index	3.46	2.81	3.46
Water quality class	IV	IV	IV

The table 4 shows that for all three years of water research in the Vidsichne reservoir, the pollution index is within 2.80-3.50, which corresponds to the fourth quality class. This means that the water is polluted and under significant anthropogenic influence, the level of which is close to the limit of sustainability of ecosystems. The dynamics of changes in the presented indicators over the years (figure 2) shows a consistently high concentration of manganese in the reservoir.

With a further increase in the concentration of manganese in the water, the ecosystem may lose its balance.

To establish the ecological coefficient of water quality in the reservoir, a model-map with scales-radii for the manganese ingredient was built. The value of dividing such a diagram is the maximum allowable concentration of manganese in drinking water, which is 0.05 mg/dm^3 and the number of axes corresponds to the average annual value of the indicator in 2019, 2020, and 2021 years of the study, respectively ($\bar{C}_{Mn,2019}$, $\bar{C}_{Mn,2020}$, $\bar{C}_{Mn,2021}$). For each indicator, according to the methods described above, average annual arithmetic values were calculated (table 5).

The central shaded circle with a radius corresponding to the MPC value is the ecological optimum. All values of average annual concentrations of manganese that fall into this area correspond to standards for drinking water. The other shaded area is the actual

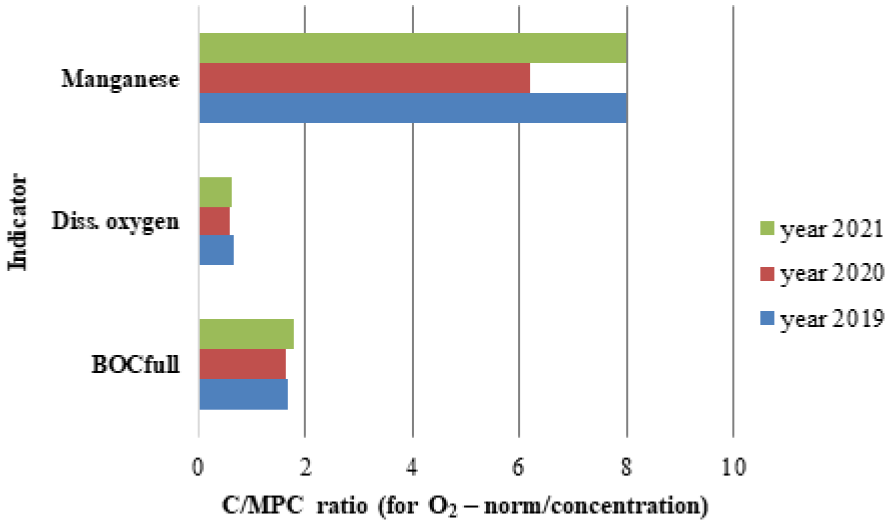

Figure 2. Dynamics of changes in the investigated water quality indicators in 2019-2021.

Table 5. Average annual arithmetic values of the investigated indicators.

Indicator	Average annual values of indicators in 2019	Average annual values of indicators in 2020	Average annual values of indicators in 2021	MPC, mg/dm^3
BOC_{full}, mg O_2/dm^3	4.95	4.91	5.31	3.00
Dissolved oxygen, mg/dm^3	9.01	10.08	9.73	6.00
Manganese, mg/dm^3	0.40	0.31	0.40	0.05

manganese concentration values. Since the indicators are outside the circle, this indicates water contamination with manganese and non-compliance of water quality with regulatory requirements.

Figure 3 presents a model map of manganese for the water of the Vidsichne reservoir. According to the methodology, to calculate the environmental factor of water quality, the following were calculated: F_{fact} – the area of the diagram, limited by the actual values of average annual manganese concentrations, and F_{optim} – the area of the diagram, limited by the optimal value of manganese concentration in water (formula 3). Plotting the actual change in hydrochemical characteristics on the diagram shows the state of the river water, which can be used to consider possible sources of pollution, and the ratio of the area occupied by the diagram of actual pollution to the area occupied by the optimal values of the standardized indicators gives ecological coefficient of water (K_e, formula 2). The values of the first class of ecological classification of the quality of surface water are taken as the optimum. Water quality class: I – very clean – < 0.3:

$$F_{optim} = \pi \cdot 0.3^2 = 0.28.$$

The area of the figure occupied by the diagram of actual contamination, which is the area of the formed triangle, is $F_{fact} = 1.52$. Thus, according to (2), the ecological coefficient of water quality is equal to 5.4. This indicates that manganese contamination of water exceeds regulatory requirements by 5.4 times:

$$K_e = \frac{1.52}{0.28} = 5.4.$$

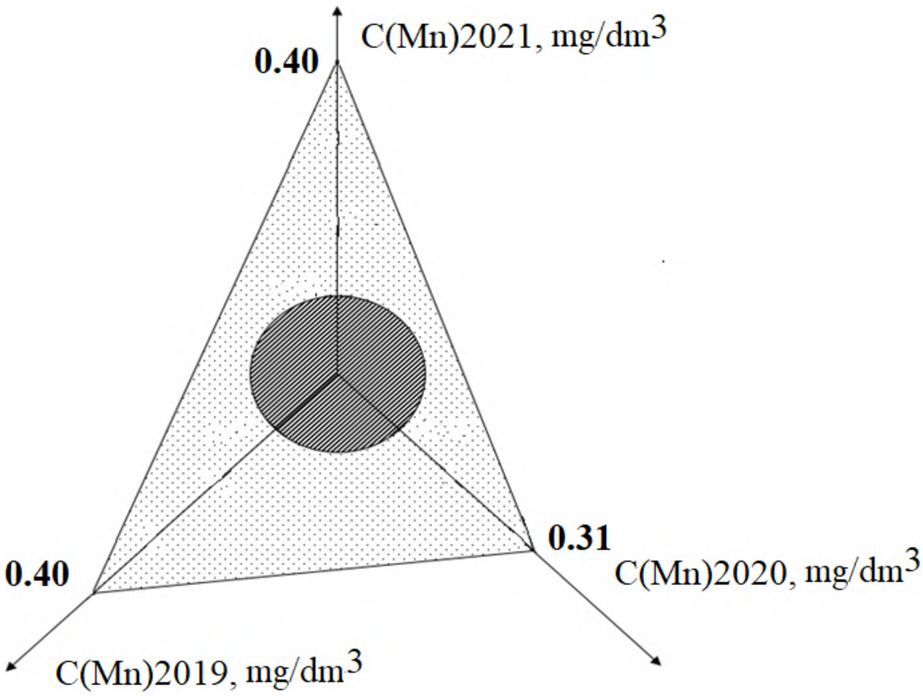

Figure 3. Model map for calculating the ecological coefficient of water quality.

The level of water quality was established according to the method described above for manganese, as the most influential ingredient on the quality of surface water in the reservoir. The calculated value of repeatability of cases of exceeding the MPC is 83% compared to the total number of results (formula 4). This indicates that manganese contamination is dominant, that is, it is characteristic, as the repeatability value is in the range of 50–100%. Such pollution corresponds to the following partial evaluation points (table 3): 1) conditionally expressed – d; 2) absolute values – 4 points.

The second level of classification is based on the establishment of the indicator of the frequency of exceeding the MPC for manganese, as the ratio of the average value of the concentration of manganese over three years to its maximum permissible concentration (formula 5). Calculations showed that the value of the multiplicity of exceeding standards is within 2-10, which corresponds to the average level of pollution, the qualitative expression of which is the following partial evaluation points: conditionally expressed – b_1; absolute values – 2 points. When combining the first and second stages of water classification, we get that the characteristic pollution of the average level is evaluated by generalized points: conventionally expressed – $d \cdot b_1$; absolute values – 8 points. And this means that the water in the Vidsichne water intake is highly polluted with manganese (table 3).

All three considered methods of studying the quality of drinking water make it possible to establish the compliance of water with current regulatory standards. They can be used to establish the ecological character of drinking water by any ingredient [12].

Recently, in the conditions of global climate changes, high temperature indicators, there is a constant increase in the manganese content in the reservoir due to a decrease in the dissolved oxygen content. Further studies showed a direct dependence of this indicator on water temperature (figure 4). Using the method of least squares, we obtained the dependence of Mn concentration (y, C(Mn), mg/dm^3) on temperature (x, °C) in the form of an approximation: $y = ax^3 + bx^2 + cx + d$, where $a = 2.65 \cdot 10^{-4}$ mg/dm^3 °C^3, $b = -6.472 \cdot 10^{-3}$ mg/dm^3 °C^3, $c = 4.461 \cdot 10^{-2}$ mg/dm^3 °C^3, $d = 1.17 \cdot 10^{-1}$ mg/dm^3 °C^3 (figure 4).

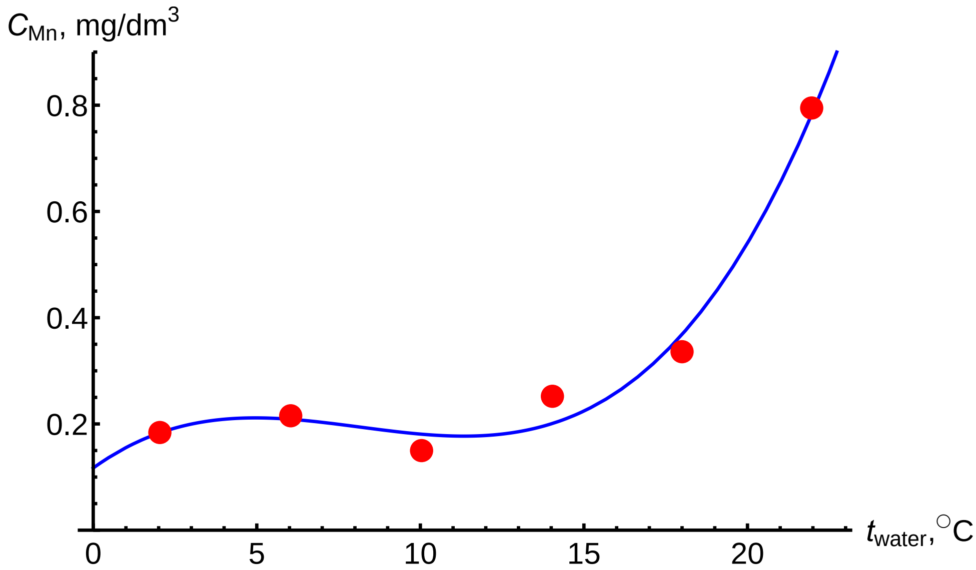

Figure 4. Dependence of manganese content on water temperature

The R^2 approximation reliability value is 0.9831. The assessment was carried out using the Excel program.

The built mathematical model indicates a significant increase in manganese content at temperatures from 14°C to 22°C and higher. At elevated temperatures, the concentration of manganese in water reaches values that are 15 times higher than the standard values.

4. Conclusions

The developed procedure for assessing water quality in natural waters allows us to conclude that the water of the Vidsichne reservoir is characterized by unstable quality. According to the content of manganese, the water belongs to the fourth quality class, that is, it is polluted.

It is reasonable to carry out a quantitative assessment of surface quality based on the following indicators: water pollution index, ecological pollution coefficient and water quality level. The graphical method of comprehensive assessment of the state of water is the basis for calculating the ecological coefficient in any reservoir.

The constructed model-map of manganese concentration for the Vidsichne reservoir indicates water pollution, and the environmental quality coefficient – a 5-fold excess of environmental standards. Mathematical processing of the results of chemical analysis of manganese concentrations during the year showed that the manganese content in water increases with increasing air temperature.

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References

[1] Verbetska K Y 2011 *Bulletin of the National University of Water Management and Nature Management* **5**(11) 91–99

[2] Kotsiuba I G, Skyba G V, Skurativska I A and Lyko S M 2019 *Methods and Objects of Chemical Analysis* **14**(4) 200–207 URL https://doi.org/10.17721/moca.2019.200-207

[3] Skurativska I, Skurativskyi S, Popov O, Viktoriia D, Mykhliuk E and Dement M 2022 Complex oxygen regimes of water objects under the anthropogenic loading *Systems, Decision and Control in Energy III* ed Zaporozhets A (Cham: Springer International Publishing) pp 317–334 ISBN 978-3-030-87675-3 URL https://doi.org/10.1007/978-3-030-87675-3_20

[4] Berka C S 1996 *Relationship between agricultural land use and surface water quality using a GIS: Sumas River Watershed, Abbotsford, B.C.* Ph.D. thesis University of British Columbia URL https://doi.org/10.14288/1.0086974

[5] 1996 Environmental Indicators of Water Quality in the United States Tech. Rep. EPA 841-R-96-002 United States Environmental Protection Agency, Office of Water (4503F) URL https://tinyurl.com/2p9hz392

[6] 2000 *Official Journal of the European Communities* **L 327** 0001 – 0073 URL https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32000L0060

[7] Arkhipchuk V V and Malinovskaya M V 2000 *Chemistry and water technology* **22**(4) 428–443

[8] Pinto I, Rodrigues S, Lage O and Antunes S 2021 *Ecotoxicology and Environmental Safety* **208** 111583 ISSN 0147-6513 URL https://doi.org/10.1016/j.ecoenv.2020.111583

[9] Qin G, Liu J, Xu S and Sun Y 2021 *International Journal of Environmental Research and Public Health* **18**(4) 1873 ISSN 1660-4601 URL https://doi.org/10.3390/ijerph18041873

[10] Thorne O and Fenner R A 2011 *Water and Environment Journal* **25**(1) 74–87 URL https://doi.org/10.1111/j.1747-6593.2009.00194.x

[11] Tyagi S, Sharma B, Singh P and Dobhal R 2013 *American Journal of Water Resources* **1**(3) 34–38 URL http://pubs.sciepub.com/ajwr/1/3/3

[12] Snizhko S I 2010 *Evaluation and forecasting of the quality of natural waters* (Kyiv: Nika Center)

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Digital economy: place of Ukraine in global trends of sustainable development

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Digital economy: place of Ukraine in global trends of sustainable development

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Abstract. The research of the Ukraine's place in global trends of sustainable development from the position of digital economy is presented. An economic essence of digital economy and its significance for Ukraine is studied. Its main components are defined. The relationship between the digitalization of the economy and the level of sustainable economic development is substantiated. Considering the fact that the development of the digital economy is characterized by a large number of indicators at the global level, the Global Connectivity Index is chosen to analyze the relationship with the SDGs achievement. The hypothesis about the dependence of SDGs achieving on the possibilities of the digital economy is confirmed with the help of mathematical modeling using correlation-regression analysis. The analysis of the relationship between Global Connectivity Index and SDGs Index is conducted. The level of influence of GCI component groups (broadband, cloud, AI, IoT) on the levels of SDGs is determined. Based on the analysis two components of the GCI index – the Internet of Things and the state of the broadband Internet, which have a significant impact on the level of SDGs achievement, are identified by the authors. It was found that two other components – the development of artificial intelligence and cloud technologies have a moderate impact on SDGs achievement. The global map of the digital technologies development level in compliance with the SDGs achievement is presented. Visualization on the map makes it possible to group countries with a high level of digitalization and achieving the SDGs on the one hand, and a high level of digitalization and relatively low indicators of sustainable development on the other hand, and vice versa. The analysis of Ukraine's place on this world map is performed. The role of digital transformation in achieving of the defined SDGs is identified.

1. Introduction

Ukraine is one of the largest European countries in terms of territory and population being at the same time quite poor from a financial point of view. Unlike other countries in the world it is rather slow in carrying out key reforms, in particular tax, land and labor market reform, etc. Until now, the period of transformation to a market economy has not been properly completed, and acceptable conditions for attracting investments and conducting business have not been created. Since 1991 the state's population has decreased by more than 10 million people. The main factors of the demographic crisis which we can now observe are, first of all, war with Russian invaders and martial law, the excess of mortality over the birth rate and population migration from Ukraine. These reasons as well as weak economic and social development, the inability to ensure a high standard of living led to the fact that many Ukrainians decided to leave the country. Labor migration causes losses to the Ukrainian's economy.

But simultaneously Ukraine is characterized by high growth rates of the IT sector – 20-35 % annually. The developed IT industry is quite an considerable factor in the growth of technological efficiency of the Ukrainian's economy. This industry is export-oriented (more than half is exported to the USA). Computer services account for almost 25 % of all services exports of Ukraine. The export share of IT in the total structure of exports is almost 7 % and it shows annual growth. The growing demand for digital technologies, cloud data storage, and cyber security can become a powerful driver of the further growth of the domestic IT sector. It is necessary to underline that many residents of the country who emigrated continue to work for Ukraine while working abroad online. The full-scale military aggression of the Russian invaders did not slow down the pace of transformation of Ukraine's digital environment. Over past 20 years the digital economy development is supposed to be one of the predominant factors that have influenced a significant increase in labor productivity in the global economy and also contributed to improved access to quality public and social services.

Ukraine invests only 0.5 % of GDP in R&D centers. This is three times less than the indicators of Poland and five times inferior to the indicators of Hungary. The low level of investment in innovative developments creates a more than 3-fold gap in labor productivity with neighboring EU member states [1]. A significant barrier to the digital economy development of Ukraine is digital divide, which includes such components as: technological, competence, economic, financial, and physical. It makes it impossible to realize the rights and responsibilities of citizens by limiting access to technologies, competences, means of digital production and interaction. In the conditions of the digital economy there is an opportunity to form and develop skills in the usage of digital technologies, their individual aspects, phenomena and processes as well as the use of relevant tools to substantiate optimal decisions, including solving complex economic tasks.

In the conditions of the digital economy the structure of business is changing in the form of its management, the cooperation with other counterparties is being established in other ways. As aptly noted by TechCrunch, the Uber company, although it is the largest, does not own any vehicles. The Facebook network does not directly create its own content. Alibaba, as the most powerful platform for sales, does not have its own products that can be sold. This indicates that something really interesting is now happening [2]. Digitization of life activities as a necessary technical condition of the contemporary global economy is the main tool that ensures its development. In the process of transition to sustainable development the task of mandatory consideration of the environmental factor necessarily arises. To properly ensure the sustainable development of society, the ecology of the environment should not be disturbed, the natural basis for the reproduction of human life should be preserved. Nowadays the main goal of sustainable development ensuring is dynamic socio-economic growth and the preservation of the environment, rational usage of the existing potential of natural resources to meet the needs of the present and future generations as well as development of an effective economic system etc. Sustainable development requires the presence of several vectors, including nature, production and society. It targets business to operate without harming the environment with effective financial indicators at the same time [3].

A total of 17 positions are allocated to the goals of sustainable development (SDGs). Undoubtedly, the role of digital transformation in Ukraine in SDGs achievement is significant. It will be investigated in this work. However, it should be noted that, in turn, the implementation of some of the SDGs will also contribute to the improvement of a current level of the digital economy of Ukraine.

2. Literature review

Under the conditions of the globalization next wave priority is given to the progressive digital economy in the development of the country. Its key factor is information, knowledge and ways of accessing them. Being a virtual environment the digital economy is able to complement the existing reality of today. Of course, it has a lot in common with the traditional economy. It is often difficult to draw boundaries between them. There is still no single definition of it agreed upon by the international community. In the vast majority of foreign sources, the emphasis is on the description of technologies and methods of interaction between economic agents when somebody is interpreting the digital economy. At the same time, specific types of technologies are often noted and certain forms of changes in economic processes are indicated. Sometimes the actual definition of the digital economy is replaced by a list of directions of its influence on economy or social sphere. It is worth noting that there is still no single concept of building a digital economy in Ukraine.

The concept of the digital economy in modern economic realities and the description of its boundaries will make it possible to create a multifunctional system of statistical measurements for its continuous monitoring of the digital economy, substantiation and evaluation of the digitalization policy. The term of digital economy first appeared in in the second half of the nineties of the twentieth century. In these years works of Tapscott [4] and Negroponte [5] were published. This term became widespread, the concepts of Web, Network, New and Internet economy. This term acquired a specific meaning. Digital economy began to develop in the late 1950s, and since the 1960s, digital innovation has been actively spreading around the world. The next (second) stage of digitalization is associated with the worldwide spread of mobile communications and the Internet which is characteristic of the mid-90s of the 20th century. In definitions of the digital economy by Tapscott the emphasis is placed on the Internet as its main component [4].

Supporting this position, we note that the main resource of knowledge in the period of the digital economy is information, if it has the characteristics of accuracy, reliability, timeliness. It is obtained precisely with the use of the Internet. The virtual network of the Internet traditionally serves as the basic platform for the digital economy progress. In recent years significant changes took place in human life. Thanks to the use of smart things, technology of blockchain, industrial Internet of things, the production process and forms and management models have also changed. Now the digital economy, based on digitization and its own specifics makes it possible to overcome spatial and sectoral limitations. It is impossible without financial technologies (FinTech), the Internet of Things (IoT), e-commerce, digital marketing (Digital Marketing) and principles of e-business management.The development of intelligent systems connected to the Internet of Things can create unique opportunities to strategically address challenges related to the UN Sustainable Development Goals to ensure a just, environmentally sustainable and healthy society [6].

The next stage of digitization that we are currently observing is connected with the proliferation of digital currencies. Various digital currencies (bitcoins and others) have already confidently won their place on the global financial market, their quantity (as well as the scale of operations with them) is increasing. This led to the formation of a new currency component of the financial world architecture that meets the requirements of the times. They have been in use since 2009 and in 10 years have proven their demand and importance. The classic understanding of the digital economy is that it is an activity the production key means in which are digital data and the mechanism of their usage. This makes it possible to significantly strengthen the efficiency or productivity of various economic activities. The economy, which involves the usage of digital technologies or services, is also called digital. In the interpretation of the essence of the digital economy by the Australian government, attention is drawn to the fact that it is a global network of activities, in particular economic and social, which is provided thanks to communication and information technologies.

The digital economy necessarily uses devices that we deal with every day, for example, phones and laptops. It allows you to quickly find the best place for rest or entertainment, quickly receive important information from a friend, etc. When paying for goods, you can use credit cards. Its mechanisms are also may be used during treatment. Companies that conduct business using elements of the digital economy are able to improve cooperation with contractors, buyers or suppliers. Digital economy is supposed to be a key driving force provoking economic growth. Bahl claims that this has profound consequences for doing business in the regions [7]. The definition of the digital economy provided by Bukht and Heeks is vague, somewhat blurred. We accept that it is based on digital services or goods, but we do not agree that it is part of the economic result [8]. Kolyadenko examines the digital economy as such, which is based on the manufacture of electronic services, goods and the spreading of them using e-commerce (computer networks) [9]. Veretiuk and Pilinskyi draws attention to the fact that the computer platform serves as a means to which the digital economy transforms all information knowledge as well as resources [10].

The digital economy is considered to be basis of the Industrial Revolution (Fourth) while the change in the general technology is clearly visible and there are signs of a change in the techno-economic paradigm. The modern phase of the industrial revolution is connected with the progress of Internet communication technologies, which have significantly changed the technology of business processes and received the name "digitalization". Summarizing existing definitions of digital economy, it should be noted that in most the component approach of definitions prevails.

Mesenburg distinguish such three component parts of digital economy: auxiliary infrastructure; e-business (conducting business activities through network); e-commerce (distribution of goods, products and services using the Internet) [11]. Therefore, the most successful, to out mind, is the following definition: digital economy is an dynamical innovative economy which is based on the innovations and information implementation as well as communication technologies in various types of economic activities and spheres of society life, which in turn makes it possible to increase the effectiveness, strength and competitiveness of various companies and the standard of population living in general. Digital transformation fundamentally converts areas and business processes based on the Internet and innovative digital technologies, that is, it is not limited to the implementation of information technologies. The digital economy is capable to significantly change existing business processes [12]. The modern Industry 5.0 system puts a human-centered approach at the center of the production process and uses innovative technical advances to ensure sustainable and sustainable intelligent production [13].

The digital economy is a driver for development and accelerating worldwide economic progress, increasing the level of labor productivity, creating new markets and types of economic activity. This is confirmed by the cooperation between the G20 countries, which are actively involved in the development of the digital economy. The digital economy definitely creates opportunities for sustainable and inclusive growth [14]. Those countries and associations that plan, gradually and systematically build the foundations of leadership and actively join the mechanisms of the digital economy achieve accelerated economic development at a faster rate. The progress of digital economy in general involves a significant transformation of labor market, which is characterized by complexity. This process is taking place gradually, because an increasing number of traditional sectors of the economy involve elements of the digital economy in activities conducting. It is worth emphasizing that the consept of "digital shadow economy" is also wide spread in the world. For example such its components are researched by scientists, as determinants of consumers' illegal behaviour online [15].

It has been established by Gasparėnienė et al that the digital shadow economy is an illegal operation in the Internet used to generate illicit cash flows for suppliers of goods/services or buyers. It allows to avoid officially declared income, because it can be not calculated and not accounted [16]. Research by these authors is a substantial contribution to the theory evolution of digital economy in general. It shoud be also pointed out that digital economy is a priority component of an innovative economy. As Pavelko et al note, formation of innovative economics should be aimed at reduction the cost of production, developing high-quality products, advance of human life and elevation it to a qualitatively brand new level [17]. The new products at the same time involve various innovative digital technologies types and forms.

The digital economy has a specific feature. It is related to the on-demand economy, that is, when using it, there is no sale of services, goods and access to them specifically at that moment when they are required. Receiving orders are placed online, and their fulfillment – offline. The advantages of the on-demand economy are the next: high velocity of obtaining the required services or goods; a decrease in their value for the end user due to a reducing in the number of intermediaries on this path; simplifying the exit of goods and services suppliers to users. Digital economy for its successful formation needs effectively functioning of three components: regulatory and legal framework that would contribute competition and entering the market for enterprises, allowed companies to fully use digital technologies; skills which are required by employees for use possibilities of digital technologies; effective establishments which use the Internet in order to increase rights and enlarge opportunities of citizens. It should be noted that in current conditions of the digital economy development digital skills as well as innovations and competitive advantages are key to achieving individual success [6, 18–21]. From the macro level point of view we speak about the level of society digitalization and smart cities [22, 23]. The digital economy acts not only as an effective foundation for the progress of public administration system, sphere of society, business, economy, the but also contributes to the achievement of a whole sustainable development, which will be confirmed in this article.

According to UNESCO sustainable development is "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." Corejova and Chinoracky [24], Laitsou et al [25] agree that the digital economy can be seen as a tool for expanding economic growth which, in turn, is part of the concept of sustainable development. Many researchers point to a positive connection between the development of the digital economy and sustainable development. Frey noted that the development of the digital economy can provide a sustainable development stimulus for economic growth [26]. Skliarov and Prokopov note that the development of the digital economy will transform the traditional economy from a resource-consuming economy to a resource-creating economy [27]. The intensive development of the digital economy not only provides spatial growth momentum for the region, but also helps to promote the economic growth of neighboring regions and ultimately forms regional coordination and sustainable development [28]. The role of infrastructure is undeniable in the growth process of any economy, as it helps to diversify production, expand trade, overcome the pressure of demographic and environmental problems and ultimately improve the quality of human life [29].

International analytical agencies also pay great attention to the relationship between digital technologies and sustainable development. Huawei's report "Accelerating SDGs through ICT" shows that SDG 4 (Quality education), SDG 3 (Good health and well-being) and SDG 9 (Industry, innovation and infrastructure) with 73 %, 71 % and 65 % respectively have the highest the level of interconnection with the development of digital technologies. The report also emphasizes that even small technological improvements can lead to better achievement of the aforementioned SDGs [30]. However, digital transformation also increases inequality and undermines social cohesion, given the gap between countries with access to the Internet (over 80 % of the population in developed countries) compared to developing countries (45 %) [31]. For developing countries that are lagging behind the most, SDG 1 on poverty reduction and SDG 5 on gender equality are most relevant. In the future, the digital economy is potentially the largest and most important opportunity for dynamic change in sustainable development worldwide [32–35]. In addition, digitalization is seen as a key driver of transformative environmental change and innovation in the next decade [36].

Countries are innovating and transforming practice by adopting and adapting the DPG. Such DPGs as digital payment solutions, data transfer protocols or digital health services can be included to improve the delivery of public services in a safe, reliable and inclusive way. Properly assembled, DPGs can create a digital public infrastructure that is powerful enough to ensure societal impact for current and future generations [37]. Zhuge et al conclude that new enterprises can deepen their competitive advantages by improving their digital capabilities, which leads to improved performance in terms of environmental, economic and social benefits and promotes sustainability. Green knowledge creation acts as a mediator between digital capabilities and sustainable development [38]. Understanding the relationship between the SDGs and digitalization allows for the development and coordination of national digital economy policies and programs that contribute to better sustainable development [39].

Imran et al [40] show that the digital economy does not always have a positive effect on sustainable development. Thus, 4G coverage and mobile broadband have been found to be positive in terms of impact on SDGs. Total Fixed Broadband Coverage and Fixed VHCN are significant but have a negative impact on SDGs. ICT professionals and ICT graduates were significant variables that negatively affect the SDGs. Use of Internet services has the largest number of subdimensions, five of which are significant. These are: news, social networks, online courses, banking and shopping. The first two have a positive effect on SDGs, and the last three have a negative effect [40]. While synergies between digitization and sustainable development are generated in aspects related to economic and social sustainability, trade-offs arise in areas related to environmental protection, such as climate change, depletion of natural resources and waste generation due to their negative connection with existing models of economic development [41]. Also, digitalization may contradict a just transition to sustainability if the digital regime is not reoriented towards inclusive practices, democratic governance and environmental regulation [42].

The paper's hypothesis is that the development vectors of global digital economy are closely correlated with the sustainable development goals. Taking into account the fact that the SDGs achievement is related to the level of digital transformation, we will perform an analysis of the relationship of individual indicators at the global level. We will also investigate the role of Ukraine's digital transformation in SDGs achievement.

3. Material and methods

The main evaluation systems of digital development indices include the European Union (EU) Digital Economy and Society Index, the Organization for Economic Co-operation and Development (OECD) digital economy indicator system, the World Economic Forum (WEF) Network Readiness Index (NRI), the Digital Evolution Index (DEI); Digital Adoption Index (DAI); ICT Development Index (IDI); Global Innovation Index (GII); economy digitization index (Boston Consulting Group – e-Intensity); the world digital competitiveness index (IMD World Digital Competitiveness Index – WDCI). A commonly used tool is the Digital Economy and Society Index (DESI).

Given that digital technologies and global connectivity are comprehensive and deep, the Global Connectivity Report is published annually, which provides a detailed analysis of global digital connectivity and its mechanisms. The Global Connection Report 2022 provides analytical data on digital development of society by countries, regions, categories of population, gender, etc. [43]. The global connection index (GCI) can be considered as an indicator of the digital economy development. GCI provides an opportunity to analyze a wide range of ICT infrastructure. The index was calculated for the first time in 2014. 79 countries are involved in the calculation, each of which calculates 40 indicators of development of digital technologies, the impact of information systems development on economic growth. The 40 indicators can be analyzed both vertically (Supply, Demand, Experience, Potential) and horizontally (Broadband, Cloud, IoT and AI) [44].

The UN Sustainable Development Agenda for the period up to 2030 envisages 17 SDGs in the global system. They aim to solve fundamental problems such as ending poverty and hunger, protecting the planet and ensuring peace. The SDGs are also aimed at other priorities, in particular the prevention of climate change, economic inequality, the development of innovations, sustainable consumption, peace and justice [45]. Through the definition of the SDGs Index, for each country, a total score characterizing the level of SDGs achievement, is determined. The maximum score – 100 points – corresponds to the achievement of all SDGs [46]. Given the fact that achieving of the SDGs is largely related to the level of digital transformation, it is advisable to analyse the relationship between these indexes at the global level and to determine which of The Four Technology Enablers have an impact on SDGs achieving. The values of the indices for each country, which are the basis for analysis of the relationship, are given in the table 1.

Table 1: GCI and SDG Index indicators (2020), based on [44, 45].

Country	GCI Total	GCI Broadband	GCI Cloud	GCI AI	GCI IoT	SDG
Algeria	32	44	24	21	24	70.9
Argentina	45	56	59	30	33	72.8
Australia	72	98	54	39	57	75.6
Austria	66	78	39	39	69	82.1
Belarus	46	64	33	21	30	78.8
Belgiu	66	83	54	42	51	82.2
Brazil	47	59	42	27	30	71.3
Bulgaria	52	65	36	24	27	73.8
Canada	70	95	54	39	48	79.2
Chile	55	68	51	30	45	77.1
China	62	84	66	48	42	72.1
Colombia	42	41	42	30	33	70.6
Croatia	51	63	36	24	39	80.4
Czech Republic	57	72	39	30	42	81.4
Denmark	77	90	57	48	78	84.9
Ecuador	38	42	30	30	33	72.5
Egypt	36	41	30	24	31	68.6
Estonia	61	78	36	33	45	81.6
Finland	76	89	63	42	75	85.9
France	70	89	54	45	57	81.7
Germany	70	78	51	45	66	82.5
Greece	52	69	39	24	48	75.4
Hungary	54	65	42	30	36	78.8
Ireland	69	74	63	60	51	81
Italy	60	78	39	36	63	78.8
Japan	75	99	57	36	69	79.8
Jordan	35	30	30	21	27	70.1
Kazakhstan	47	65	36	24	27	71.6
Lithuania	58	80	39	24	36	76.7
Luxembourg	70	77	54	42	51	74.2

Continuation of table 1

Country	GCI TOTAL	GCI BROADBAND	GCI CLOUD	GCI AI	GCI IoT	SDG
Malaysia	53	63	36	27	39	70.9
Mexico	43	53	42	27	33	69.1
Morocco	38	39	42	21	24	70.5
Netherlands	75	81	63	51	75	81.6
New Zealand	72	96	60	33	54	79.1
Norway	73	95	51	42	81	82
Oman	48	60	39	21	36	70.1
Peru	40	48	39	30	30	71.1
Poland	51	65	36	30	33	80.2
Portugal	61	87	39	30	48	78.6
Romania	50	69	39	24	30	75
russia	50	72	36	27	33	73.8
Serbia	45	48	36	24	30	75.6
Singapore	81	98	87	45	54	69.9
Slovakia	54	75	36	24	36	79.6
Slovenia	56	71	36	27	39	81.6
Spain	61	80	39	30	54	79.5
Sweden	80	98	69	42	78	85.6
Switzerland	81	101	63	45	69	80.1
Thailand	46	60	36	30	33	74.2
Turkey	46	60	36	24	27	70.4
Ukraine	43	51	33	24	30	75.5
UAE	62	86	36	33	39	70.2
United Kingdom	75	80	63	48	69	80
United States	87	96	93	54	75	76
Uruguay	50	66	42	27	42	74.5
Vietnam	41	59	30	27	33	72.8

The hypothesis that the achievement of the SDGs depends on the capabilities of the digital economy can be confirmed using mathematical modeling, that is, its expression through a regression equation. Regression analysis will make it possible to draw reasoned conclusions about the relationship of the studied quantities, which are based and supported by specific mathematical calculations. In the case of the relationship between GCI indices and SDGs it is advisable to analyze the degree and nature of the influence of each of the groups of GCI components (broadband, cloud, AI, IoT) on the level of SDGs as well as to conduct such an analysis in the form of a multivariate correlation analysis, which evaluates the strength of the relationship between the studied variables

Using a multiple regression analysis it is possible to select a multivariate statistical model and to describe the form of the relationship between the factors. A multivariable linear regression model with m independent (factor) variables will look like this:

$$Y_t = a_0 \cdot x_{i0} + a_1 \cdot x_{i_1} + a_2 \cdot x_{i_2} + a_3 \cdot x_{i_3} + \sum i \quad (1)$$

where x_{ij} are the factor variables – broadband, cloud, AI, IoT; i – number according to the order of the object in the population being studied, $i = 1, 2, \ldots, n$; $\sum i$ – a random error that has a mathematical expectation of 0 and a variance q_2; x_{i0} – dummy variable equal to 1 in all observations.

In this model the parameters a_{ij} to be estimated are unknown.

Regression statistics calculated from the original data are shown in table 2.

Table 2. Regression statistics

Multiple R	0.765531723
R Square	0.586038819
Adjusted R Square	0.554195652
Standard Error	3.180923684
Observations	57

As can be seen from the above data there is a close relationship between the SDGs and the GCI. The correlation coefficient of 0.7655 between the specified arrays of data indicates a close direct connection between the global level of sustainable development and digital transformation.

Correlation coefficients of individual components of GCI with SDG are given in table 3.

Table 3. Correlation coefficients

	Broadband	Cloud	AI	IoT
SDG	0.611104	0.312098	0.503799	0.699281

The results of analysis of variance are shown in tables 4, 5.

Table 4. Analysis of variance (part 1).

	df	SS	MS	F	Significance F
Regression	4	744.863359	186.2158	18.40391	1.78425E-09
Residual	52	526.1503253	10.11828		
Total	56	1271.013684			

Table 5. Analysis of variance (part 2)

	Coefficients	Standard Error	t Stat	P-value	Lower 0.95	Upper 0.95
Intercept	66.8172	1.9061	35.0548	0.0000	62.9924	70.6420
Broadband	0.0839	0.0403	2.0798	0.0425	0.0030	0.1648
Cloud	-0.1695	0.0548	-3.0914	0.0032	-0.2796	-0.0595
AI	0.0825	0.0913	0.9031	0.3706	-0.1008	0.2657
IoT	0.1921	0.0512	3.7524	0.0004	0.0894	0.2948

The estimation of the parameters based on the results of the correlation-regression analysis indicates the adequacy of the obtained model. The analysis of correlation coefficients makes it possible to determine the degree of influence of digitalization factors on SDGs achieving.

We can see that the highest level of influence (coefficient 0.699) has the level of development of the Internet of Things. This situation can be explained by the fact that the spread of such achievements of the digital economy as sensors hat transmit information to databases for managing people's habitat, strengthening the interconnection between various devices that accelerate management processes, make it possible to solve environmental problems quickly, control the state of air and water, expand the possibilities of agriculture to overcome the problems of poverty, etc. The state of broadband Internet also has an important role (correlation coefficient 0.611) for the achievement of the SDGs. As the basis for the development of digital technologies the collection and transmission of information, this component directly affects the development and achievements of industry, health care, education, energy conservation, city management, etc. The development of artificial intelligence has a moderate relationship with the SDGs. We explain this by the fact that the latest achievements of artificial intelligence may not become widely distributed in a short period of time and therefore may have a certain time lag. As for cloud technologies we do not observe a significant relationship with the resulting indicator, which can be explained by the fact that cloud technologies are only a tool for storing and accessing information.

The global map of the level of digitalization in accordance with the achievement of the goals of sustainable development looks like this (figure 1).

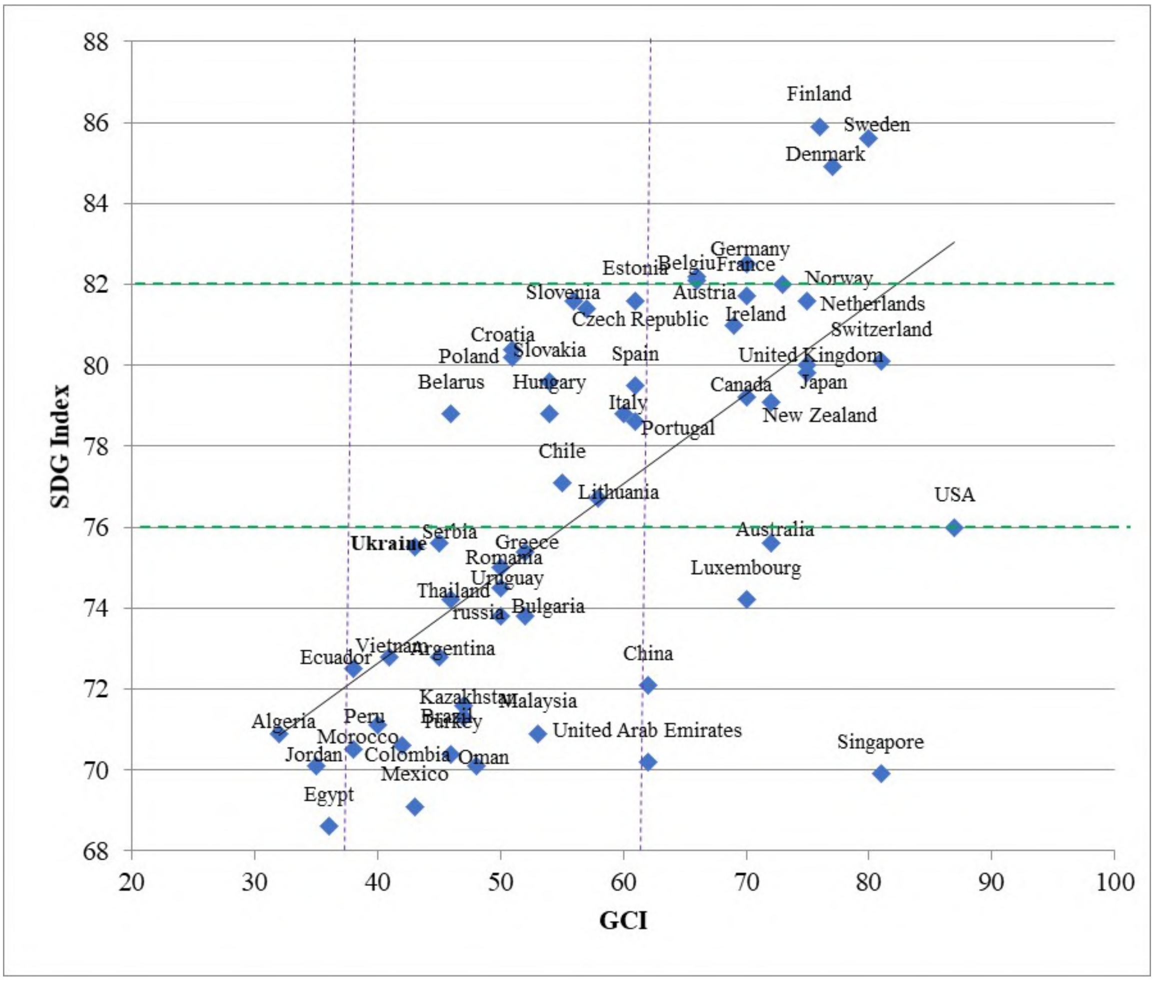

Figure 1. Global Connectivity Index and Sustainable Development Goals Index (2021).

According to figure 1 it is possible to clearly trace the three leading countries in terms of the level of digital transformation and the achievement of sustainable development goals – Finland, Sweden, and Denmark, which have the highest SDGs Indicator level and one of the highest indicators of digitalization. The group of countries with a high rating of the development of the digital economy and a sufficient level of indicators of sustainable development include mostly developed European countries (Germany, France, Norway, Austria, Netherlands, Switzerland, United Kingdom), as well as Canada, Japan, and New Zealand. A number of countries with a relatively lower rate of achievement of sustainable development goals (USA, Australia, Luxembourg, Singapore) demonstrate, however, a high level of development of digital technologies. Ukraine, with a Global Connectivity Index of 43 and a Sustainable Development Goals Index of 75.5, is in the group of countries with an average level of digital technology development and a below-average level of achievement of SDGs. However, the dynamics of Ukraine's indicators are positive both by one and by another indicator. And in terms of the level of digitalization Ukraine confidently holds the first positions in the context of the speed of progress. So, taking into account the fact that the SDGs are closely correlated with the development vectors of the global digital economy we will determine the key trends and prospects of digital transformation in Ukraine in accordance with the 17 SDGs (table 6).

Table 6: The role of digital transformation of Ukraine in achievement of the SDGs.

SDG	The impact of digital transformation
1. No poverty	Digitalization provides opportunities for the least protected sections of the population to have access to social programs through online platforms, crowdfunding, mobile applications
2. Zero hunger	Digital transformation makes it possible to improve the efficiency of agricultural production on the basis of precision agriculture, allows to ensure the openness and stability of the agricultural market
3. Good health and well-being	Digital medicine enables online interaction between patients, healthcare professionals and institutions using digital technologies through the creation of a national electronic system
4. Quality education	The digital vortex brings digital skills (competencies) to the first positions among all the skills of citizens. Learning is changing from a "know-it-all" principle to a "knowing how to learn throughout life and become self-fulfilled and competitive". Digital technologies provide much wider access to knowledge, and also contribute to the emergence of new professions
5. Gender equality	Digital transformation in Ukraine allows men and women to have equal access to information resources, and to perform various types of work that reduce the level of differentiation between men and women
6. Clean water and sanitation	The use of sensors in the Internet of Things as well as their system analysis by means of Big Data allows monitoring the state of water and its use
7. Affordable and clean energy	The analysis of Big Data obtained through a network of digital tools makes it possible to develop projects for the use of renewable energy sources, to modernize the existing energy complex with the aim of efficient use of energy resources

Continuation of table 6

SDG	The impact of digital transformation
8. Decent work and economic growth	The systemic development of "open data" is an important factor in economic growth and can affect the growth of the EU economy by 0.5–1 % [47]. If there are risks of unemployment in certain professions, the digital transformation creates new types of economic activity that give every person the opportunity to realize himself.
9. Industry, innovation and infrastructure	Innovative development through digitization is ensured by large-scale initiatives to integrate the best international ICT practices into industrial sectors. As a result, the formation of joint groups that will unite specialists of digital technologies and industry in order to develop and implement integrated products and services is predicted. This will significantly contribute to the innovative development of the industry, will allow to reduce costs and significantly increase the added value due to the use of improved digital infrastructure.
10. Reduced inequalities	The access of various strata of the population and social groups to digital technologies, in particular mobile applications, electronic platforms, remote communication, makes it possible to realize personal interests of a person, to work remotely, which reduces social inequality
11. Sustainable cities and communities	Smart City complexes, built on the basis of the interaction of IoT, Big Data Analysis, electronic platforms and other digital technologies, make it possible to make cities safer, more comfortable for residents through monitoring the quality of city air, water, traffic flow management, social services, etc.
12. Responsible consumption and production	Achieving this goal of sustainable development is largely facilitated by the development of the sharing economy, which includes shared living (coliving), shared use of cars (carsharing), offices (coworking), gadgets, clothes and even food (foodsharing). Part of this digital trend includes cloud technologies
13. Climate action	The means of the Internet of Things make it possible to monitor air quality, emissions of harmful substances, use of electricity, and take appropriate operational measures to combat climate change.
14. Life below water	The use of digital technologies allows more efficient use of marine resources for sustainable development, in particular through satellite images, analysis of large arrays of data obtained through sensors
15. Life on land	Digital control of soil quality, biodiversity, use of natural resources, promotes their sustainable use
16. Peace, justice and SI	Expanding citizens' access to digital state services, platforms, development of open data contributes to the achievement of this goal
17. Partnerships for the goals	A global partnership enabled by digitalization is bringing countries and continents together to achieve the Sustainable Development Goals. An example is Ukraine's assignment to the "Digital Europe" program, which provides financing for digitization projects

The digital agenda of Ukraine "Ukraine 2030s – a country with a developed digital economy" [48] defines the key strategic, operational directions of digital transformation, development scenarios, a list of digitalization initiatives and projects as well as ways of managing challenges associated with the specified processes.

So, the digital transformation of Ukraine, which is focused on such key digital trends as: data, which is becoming the main factor of competitiveness; development of the Internet of Things; digital transformations of economic sectors; sharing economy; virtualization of IT systems of the physical infrastructure; Artificial Intelligence; digital platforms, rapidly bringing Ukraine closer to achieving the SDGs. The full-scale military aggression of the Russian Federation not only did not slow down the pace of digital transformation of Ukraine, but also contributed to the development of all these processes with the aim of bringing Ukraine closer to victory.

In particular, it should be mentioned that the functionality and number of users of the state digital application and "Diia" portal for citizens to receive public services online has significantly expanded. The application "eEnemy" has found its usage for the identification of Russian troops on the territory of Ukraine. Another important achievement of Ukraine is that the application for electronic registration of damaged property became in demand, the idea of a digital mortgage "eOselya" became revolutionary. Thus, the volume of educational programs for the development of digital education has expanded considerably as well as the number of regional informatization programs has increased.

4. Conclusions

Consequently, the development of the digital economy at the global level and at the level of national economies significantly contributes to the SDGs achievement. It is evidenced by the results of the conducted research. According to the authors' calculations there is a close relationship between the SDG Index and the GCI.

Based on the analysis the authors identified two components of the GCI index – the Internet of Things and the state of the broadband Internet, which have a significant impact on the level of SDGs achievement. This is due to the fact that the use of elements of the Internet of Things, interconnected by digital technologies of devices and sensors, which allows the transfer and exchange of data between the physical world and computer systems in automatic mode, makes it possible to solve economic, environmental, and social problems quickly and promote sustainable development. The explanation of the close connection between broadband and the level of sustainable development is also quite simple, since the speed of accumulation and exchange of information, the use of elements of artificial intelligence and other achievements of the digital economy directly depends on its quality and coverage density. This, in turn, contributes to sustainable economic development.

The development of artificial intelligence and cloud technologies have a moderate impact on SDGs achievement. The authors explain this result by the time gap between the latest achievements of AI and their widespread introduction into social processes that would have an impact on sustainable development, simultaneously cloud technologies are only a tool for storing and accessing information.

The analysis of Ukraine's place on the world map of the digital economy development and the level of SDGs achievement leads to the conclusion that Ukraine with a Global Connectivity Index of 43 and a Sustainable Development Goals Index of 75.5 is in the group of countries with an average level of digital development technologies and below the average level of SDGs achievement. At the same time a positive dynamic is observed for both indicators.

The authors identified the key trends and prospects of Ukraine's digital transformation in accordance with the 17 SDGs and the Digital Agenda of Ukraine "Ukraine 2030E – a country with a developed digital economy". The implementation of the above prospects will make it possible to move steadily towards achieving the SDGs even during martial law.

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References

[1] 2020 Natsionalna ekonomichna stratehiia 2030 URL https://nes2030.org.ua/
[2] Deloitte 2018 *What is digital economy? Unicorns, transformation and the internet of things* URL https://www2.deloitte.com/mt/en/pages/technology/articles/mt-what-is-digital-economy.html
[3] Pavelko O, Antoniuk O, Lazaryshyna I and Los Z 2021 *IOP Conference Series: Earth and Environmental Science* **915**(1) 012026 URL https://doi.org/10.1088/1755-1315/915/1/012026
[4] Tapscott D 1994 *The Digital Economy: Promise and Peril In The Age of Networked Intelligence* URL http://dontapscott.com/books/the-digital-economy
[5] Negroponte N 1995 *Being Digital* (London: Hodder & Stoughton) URL http://web.archive.org/web/20220705034846if_/http://governance40.com/wp-content/uploads/2018/12/Nicholas-Negroponte-Being-Digital-Vintage-1996.pdf
[6] Mazurchenko A and Maršíková K 2019 *Acta Informatica Pragensia* **8**(2) 72–87 ISSN 18054951 URL https://aip.vse.cz/artkey/aip-201902-0001.php
[7] Bahl M 2016 The Future of Businesses and Jobs in Asia Pacific's Digital Economy The Work Ahead The Center for the Future of Work URL https://thoughtlabgroup.com/wp-content/uploads/2019/04/the-work-ahead-the-future-of-business-and-jobs-in-asia-pacifics-digital-economy-codex2255.pdf
[8] Bukht R and Heeks R 2017 Defining, conceptualising and measuring the digital economy Development Informatics working paper 68 URL https://doi.org/10.2139/ssrn.3431732
[9] Kolyadenko S V 2016 *Economy. Finances. Management* (6) 106–107
[10] Veretiuk C M and Pilinskyi V V 2016 *Naukovi zapysky Ukrainskoho naukovodoslidnoho instytutu zviazku* (2) 51–58
[11] Mesenbourg T L 2001 Measuring the digital economy URL http://web.archive.org/web/20230129223602if_/https://www.census.gov/content/dam/Census/library/working-papers/2001/econ/umdigital.pdf
[12] Pyshchulina O 2020 *Digital economy: trends, risks and social determinants* (Kyiv: Razumkov centre) URL https://razumkov.org.ua/uploads/article/2020_digitalization.pdf
[13] Atif S 2023 *Sustainable Development* URL https://doi.org/10.1002/sd.2542
[14] 2016 G20 Digital Economy Development and Cooperation Initiative URL http://www.g20.utoronto.ca/2016/g20-digital-economy-development-and-cooperation.pdf
[15] Shang R A, Chen Y C and Chen P C 2008 *Journal of Business Ethics* **80**(2) 349–365 ISSN 1573-0697 URL https://doi.org/10.1007/s10551-007-9424-2
[16] Gasparėnienė L, Remeikienė R and Schneider F G 2017 *Journal of Business Economics and Management* **18**(2) 273–287 URL https://doi.org/10.3846/16111699.2016.1214620
[17] Pavelko O, Zaluzhnyi A, Trofimcuk N and Prokopchuk V 2021 *IOP Conference Series: Earth and Environmental Science* **915**(1) 012013 URL https://doi.org/10.1088/1755-1315/915/1/012013
[18] Shakina E, Parshakov P and Alsufiev A 2021 *Technological Forecasting and Social Change* **162** 120405 URL https://doi.org/10.1016/j.techfore.2020.120405
[19] Benešová D and Hušek M 2019 *Entrepreneurship and Sustainability Issues* **6**(3) 1182 URL https://doi.org/10.9770/jesi.2019.6.3(9
[20] Ragnedda M, Ruiu M L and Addeo F 2020 *New Media & Society* **22**(5) 793–816 URL https://doi.org/10.1177/1461444819869604
[21] Tewathia N, Kamath A and Ilavarasan P V 2020 *Technology in Society* **61** 101251 ISSN 0160-791X URL https://doi.org/10.1016/j.techsoc.2020.101251
[22] Sá M J, Santos A I, Serpa S and Ferreira C M 2021 *Academic Journal of Interdisciplinary Studies* **10**(2) 1 URL https://doi.org/10.36941/ajis-2021-0033
[23] Komninos N, Kakderi C, Collado A, Papadaki I and Panori A 2021 *Journal of Urban Technology* **28**(1-2) 93–114 URL https://doi.org/10.1080/10630732.2020.1805712
[24] Corejova T and Chinoracky R 2021 *Sustainability* **13**(19) 11040 URL https://doi.org/10.3390/su131911040
[25] Laitsou E, Kargas A and Varoutas D 2020 *Economies* **8**(4) 85 URL https://doi.org/10.3390/economies8040085
[26] Frey C B 2015 *Scientific American* **312**(1) 12–12 URL https://doi.org/10.1038/scientificamerican0115-12

[27] Skliarov V V and Prokopov O V 2019 *Ukrainskyi metrolohichnyi zhurnal* (3) 47–56 URL https://www.researchgate.net/publication/339335517
[28] Jiao S and Sun Q 2021 *Sustainability* **13**(18) 10245 URL https://doi.org/10.3390/su131810245
[29] Beirne J and Fernandez D G (eds) *Harnessing Digitalization for Sustainable Economic Development: Insights for Asia* (Tokyo: Asian Development Bank Institute) URL https://www.adb.org/publications/harnessing-digitalization-sustainable-economic-development
[30] 2018 Accelerating SDGs through ICT 2018 Huawei ICT Sustainable Development Goals Huawei Technologies Co., Ltd. URL https://www.huawei.com/minisite/gci/assets/files/Huawei_2018_SDG_report_en.pdf
[31] Digital Watch 2023 Sustainable development URL https://dig.watch/topics/sustainable-development
[32] Besada H 2018 Digital Economy and the Implementation of the 2030 Agenda for Sustainable Development URL https://www.unsouthsouth.org/wp-content/uploads/2018/12/Digital-Economy-and-the-Implementation-of-the-2030-Agenda-Hany-Besada.pdf
[33] Huy P Q and Phuc V K 2023 *Heliyon* **9**(2) URL https://doi.org/10.1016/j.heliyon.2023.e13392
[34] George G and Schillebeeckx S J 2022 *Journal of World Business* **57**(3) 101326 URL https://doi.org/10.1016/j.jwb.2022.101326
[35] Deist M K, McDowell W C and Bouncken R B 2023 *Journal of Business Research* **161** 113827 URL https://doi.org/10.1016/j.jbusres.2023.113827
[36] Sareen S and Haarstad H 2021 *Environmental Innovation and Societal Transitions* **41** 93–95 URL https://doi.org/10.1016/j.eist.2021.09.016
[37] World Economic Forum 2022 Inclusive digital infrastructure can help achieve the SDGs. Here's how URL https://www.weforum.org/agenda/2022/09/how-inclusive-digital-infrastructure-help-achieve-sdgs
[38] Zhuge K, Lin W, Yuan Y, He H and Zhang Y 2023 *International Journal of Environmental Research and Public Health* **20**(3) 2274 URL https://doi.org/10.3390/ijerph20032274
[39] Ionescu-Feleag L, Ionescu B S and Stoica O C 2023 *Electronics* **12**(4) 961 URL https://doi.org/10.3390/electronics12040961
[40] Imran M, Liu X, Wang R, Saud S, Zhao Y and Khan M J 2022 *Sustainability* **14**(18) 11130 URL https://doi.org/10.3390/su141811130
[41] Pérez-Martínez J, Hernandez-Gil F, San Miguel G, Ruiz D and Arredondo M T 2023 *Science of The Total Environment* **857** 159700 URL https://doi.org/10.1016/j.scitotenv.2022.159700
[42] Andersen A D, Frenken K, Galaz V, Kern F, Klerkx L, Mouthaan M, Piscicelli L, Schor J B and Vaskelainen T 2021 *Environmental Innovation and Societal Transitions* **41** 96–98 URL https://doi.org/10.1016/j.eist.2021.09.013
[43] ITU 2022 Global Connectivity Report 2022 URL https://www.itu.int/itu-d/reports/statistics/2022/05/30/gcr-preface/
[44] 2020 2020 Global Connectivity Index URL https://www.huawei.com/minisite/gci/en/methodology.html
[45] United Nations 2019 Decade of Action - United Nations Sustainable Developmen URL https://www.un.org/sustainabledevelopment/decade-of-action/
[46] 2022 Sustainable Development Report 2021 URL https://2021.dashboards.sdgindex.org/rankings
[47] 2017 *DigiWorld Economic Journal* (107) URL https://en.idate.org/product/international-trade-of-digital-goods-and-services/
[48] Ukrainskyi instytut maibutnoho 2018 Ukraina 2030e — kraina z rozvynutoiu tsyfrovoiu ekonomikoiu URL https://strategy.uifuture.org/kraina-z-rozvinutoyu-cifrovoyu-ekonomikoyu.html

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Bulking of activated sludge in the biological treatment of municipal and industrial wastewater, due to the massive development of filamentous bacteria Type 021N

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Bulking of activated sludge in the biological treatment of municipal and industrial wastewater, due to the massive development of filamentous bacteria Type 021N

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Abstract. A research of the causes and consequences of bulking of activated sludge was conducted at existing biological wastewater treatment plants (municipal and local at an industrial enterprise). The filamentous bacterium that was caused the bulking of the activated sludge in the studied treatment plants was identified as Type 021N. It was established that the studied filamentous bulking causes a significant deterioration of the technological characteristics of activated sludge flocs and it is accompanied by suppression of the nitrification process. To suppress the bulking of activated sludge two methods of suppressing the inflow of hydrogen sulfide into biological treatment plants were successfully used: blowing from wastewater at municipal treatment plants and inhibiting its formation at local treatment plants in the settling and laminar flow zones.

1. Introduction

The ability of activated sludge to form strong, rapidly easy settling flocs is one of its main properties, which is used to organize the process of biological wastewater treatment in the system of aeration tank–secondary clarifier. The formation of flocs is due to the presence in the microbiocenosis of active sludge bacteria, which secrete biopolymers-flocculants. In this way, they aggregate and spontaneously separate from the treated liquid. Bulking of activated sludge is a violation of the process of separation of activated sludge from purified wastewater. This is due to the intensive development of filamentous microorganisms, which causes the losses of sludge its ability to sedimentation [1–5]. The development of such type of activated sludge leads to a decrease in the volume of excess sludge water, a deterioration in the density and water yield of the sludge, an increase in the content of suspended substances in purified water, removal of sludge particles together with purified water, and a decrease in the concentration of activated sludge in the recirculation flow until it is completely removed from the system [6–8]. Thus, bulking of activated sludge could be causing serious operational problems and increasing wastewater treatment costs.

The problem of preventing and suppressing the bulking of activated sludge is given a lot of attention by specialists, technological and microbiological studies are involved, including molecular biological studies of the mechanisms underlying filamentous bulking (the role of extracellular polymeric substances regulated by quorum sensing) [9–12]. There are four known hypotheses explaining filamentary bulking of activated sludge: the hypothesis of selection by reserve substances, the hypothesis of diffusional selection, the kinetic hypothesis, and the hypothesis of metabolic selection [8, 13].

The microflora of activated sludge is represented by unicellular bacteria, filamentous bacteria, actinomycetes, fungi, algae. Microbial cells in activated sludge can be represented in two forms: free-floating individual cells and aggregates of individual cells (flocs, biofilm), which enable individual bacterial cells to remain in the recirculation streams. The filament growth is the perfect combination of these two growth forms. In fact, filaments (trichomes) are chains of individual cells, which are characterized by almost the same mass exchange as individual cells, and the ability to stay in structures is close to flocs or immobilized biomass [1, 3, 6, 13, 14].

The peculiarities of the development of most filamentous microorganisms make it impossible to use the classical microbiological technique of species identification, which is based on obtaining first accumulating and then isolating pure cultures. There are more than 30 different types of microorganisms, mainly bacteria, that cause one or another degree of bulking of activated sludge [13,15]. Most filamentous bacteria that cause bulking do not have strict systematic names (they are not identified by indicators required by general microbiology), but have a number, because their characteristics are still poorly studied. There are 30 species of filamentous bulking-causing bacteria, about 10 species of this bacteria are caused of operational problems in biological treatment plants. The most complete and popular classification of filamentous organisms of activated sludge is proposed in [15]. Classification keys and characteristics of filamentous bacteria that cause sludge bulking are based on microscopic examination of filamentous organisms. In activated sludge, with the help of these keys, 21 species of different filamentous organisms can be identified. The classification is technological rather than microbiological, since for a number of bulking-causing microorganisms, their species affiliation has not been established. However, their main morphological features have been noted, allowing to assign them to one or another type. D. Eikelboom also notes a number of technological parameters that contribute to the development of a specific causative agent of filamentous bulking.

Activated sludge with ideal sedimentation capacity (sludge volume index 80-120 cm^3/g) always contains a certain number of filamentous microorganisms. At the same time, filamentous forms play a significant role in the creation of strong and large (100-2000 μm) flocs of activated sludge [13]. Filamentous microorganisms can affect the sedimentation characteristics of activated sludge in three ways [15]:

- Filamentous microorganisms protrude from the flocs and prevent them from being tightly connected. The structure of the flocs is not disturbed;
- The appearance of flocs with an open structure of agglomerates, which sedimentation relatively slowly and are poorly compacted. Some filamentous bacteria are formed balls of filaments.
- Filamentous microorganisms that cause the floating of activated sludge, which leads to the appearance of layers of foam.

Along with the size of the population of filamentous microorganisms, their shape and length also affect the sedimentation characteristics of activated sludge. The size of population and morphology of filamentous microorganisms are important for sludge sedimentation. But no less important factors determining the settling velocity of the flocs are their physicochemical properties [13, 16]:

- The shape of the floc. “Round” flocs settle better than flocs with an irregularly shaped flocs;
- The size of the floc;

- The structure of the floc. Compact flocs settle faster than open clusters;
- The ash content;
- The degree of bonded water by the floc (zooglyic bulking of sludge);
- The surface charge on the floc.

Some compounds in wastewater can stimulate the growth of certain filamentous bacteria because these compounds are not used by most other microorganisms (lack of competition). The most typical example of such compounds is sulfide (H_2S). Reduced sulfur compounds stimulate the development of such filamentous bacteria as Thiothrix, Type 021 N, Beggiatoa and Type 0914 [15, 17–19].

In order to overcome filamentous microorganisms, certain methods have been developed. These methods suppress or the symptoms or the cause of bulking [13, 15–18, 20]:

- Chlorination;
- Addition of hydrogen peroxide;
- Ultrasonic treatment of sludge;
- Addition of flocculants, calcium compounds, iron and aluminum salts;
- Regulation loads on sludge;
- Increasing aerobic capacity in regenerators;
- Immobilization of sludge;
- Mutagenic effects.

The purpose of the work is identification of filamentous bacteria that caused the bulking of activated sludge during the treatment of municipal wastewater and local treatment of industrial wastewater, determination of the consequences of bulking of activated sludge for the efficiency of wastewater treatment from nitrogen compounds, and the development of technological measures to suppress and prevent bulking.

2. Objects and research methods

The object of the study was the bulking activated sludge of two sewage treatment plants: municipal (object 1) and local (object 2) for the treatment of industrial wastewater of a milk processing enterprise.

Identification of filamentous microorganisms was carried out according to Eikelboom's method, which is based on the determination of the following characteristics: mobility, branching, shape of filaments, attached growth, diameter of cells, presence of transverse walls between cells, shape of cells, presence of capsules, presence of various granules [15]. Microscopy of preparations, study of activated sludge microorganisms and identification of filamentous bacteria were carried out according to [15, 21]. In the table 1 also shows methods of researching the technological characteristics of activated sludge flocs [15], which affect its sedimentation properties.

The sludge volume index and hydrochemical indicators of wastewater were determined according to the methodology recommended by the professional literature [21]. Filament index – according to the recommendations of Eikelboom [15].

3. Results and discussion

Microscopic research of bulking activated sludge samples were carried out at object 1. The research showed that the formed activated sludge flocs (generally small, weak, irregularly shaped, open structure) were almost absent. It was also noted the presence of continuous strong strands and plexuses of filamentous bacteria (the filament index reached maximum values), caused by a high concentration of filamentous bacteria of one species. When the sludge volume index

Table 1. Microbiological studies to evaluate the technological properties of activated sludge flocs and the identification of filamentous bacteria – the causative agents of bulking sludge.

Index	Method of determination
Morphological characteristics of activated sludge flok	
shape	Microscopy ×200
strength	Microscopy ×200
structure	Microscopy ×200
size	Measurements using an eyepiece micrometer
Characteristics of filamentous microorganisms	
mobility	Microscopy ×200, ×450
branching	Microscopy ×200, ×450
filament shape	Microscopy ×200, ×450
attached growth	Microscopy ×200, ×450
cells shape	Microscopy ×200, ×450
septa or transverse walls	Microscopy ×200, ×450
filament diameter	Measurements using an eyepiece micrometer
sheath	Ink staining
granules:	
– polyphosphate granules	Naisser (or Mayer) staining
– sulfur granules	Test with Na_2S
Gram +/ Gram –	Gram staining

Table 2. The results of the technological analysis of activated sludge flocs in the investigated sewage treatment plants.

Morphological characteristicsof activated sludge floc	Object 1	Object 2
shape	irregular	rounded
strength	weak	weak
structure	open	compact
size, μm	up to 200	mostly over 200
Sludge volume index, cm^3/g	800-1100	450-520
Filament index	5	4-5

exceeded 1000 cm^3/g, filamentous bulking-causing bacteria were found in sludge samples from the regenerator, which were studded with sulfur crystals. A sulfur test with these filamentous bacteria was also positive. Data on the determination of the characteristics of filamentous bacteria, necessary for their identification, are presented in 3. On the basis of these characteristics (table 2) and Eikelboom's identification keys, filamentous bacteria were identified as Type 021 N.

Since Type 021 N bacteria belong to sulfur bacteria, the presence of hydrogen sulfide (sulfides) in the incoming wastewater was considered as the main factor initiating their development. This assumption was confirmed by the data of monitoring these parameters for 1 year (figure 1). Therefore, an increase in the content of sulfides in wastewater ($\geqslant$ 1 mg/dm^3) entering the treatment plant positively correlates with an increase in the sludge volume index, i.e. development activity of filamentous bacteria Type 021N. It should be noted that hydrogen

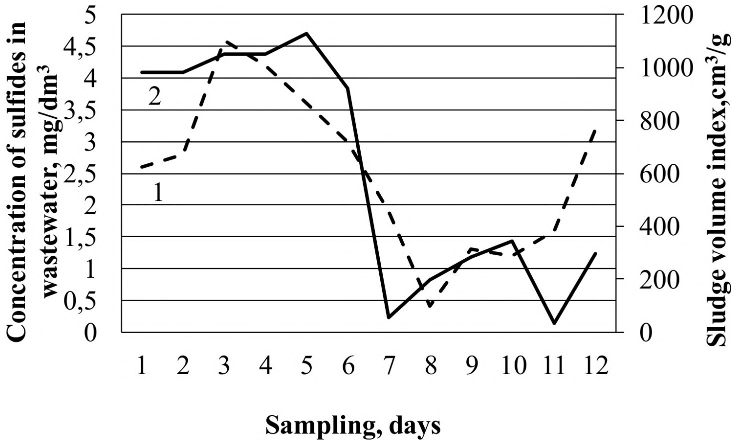
Table 3. Results of determining the characteristics of filamentous bacteria, the causative agent of activated sludge bulking (according to the Eikelboom's scheme) in the investigated treatment plants.

Index	Characteristics of filamentous bacteria	
	Object 1	Object 2
Mobility	absent	absent
Branching	absent.	absent.
Filament length, μm	over 200	over 170
Filament shape	straight	straight
Septa or transverse walls	clearly visible	visible
Attached growth	absent.	absent.
Cell shape	disc shared, there are black discs	Disc shared
Filament diameter, μm	0.9-1.5	0.8-1.2
Sheath	absent	absent
Granules:		
– polyphosphate granules	absent	present in vivo in individual samples
– sulfur granules	absent	positive
– test with Na_2S	positive	absent
Gram staining	negative	negative

sulfide in the incoming wastewater consistently exceeds the permissible content (1 mg/dm^3). The constantly high content of hydrogen sulfide in the wastewater entering the treatment plant is confirmed by the deposits of sulfur (a product of the oxidation of hydrogen sulfide by oxygen) on the walls of the channels for supplying water to the aeration tanks (before grates, after sand traps, in secondary clarifiers). Hydrogen sulfide enters to the wastewater in two ways: in the initial composition of industrial and domestic wastewater and through the formation as a result of microbiological sulfate reduction in treatment plants.

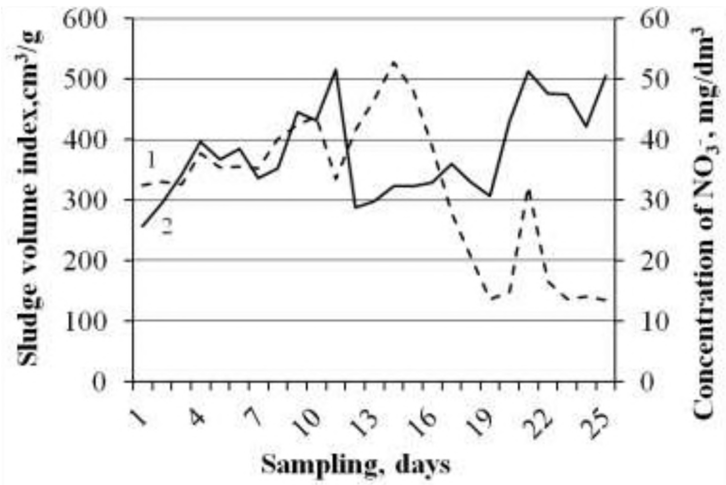
Therefore, a decrease of the sulfates concentration in wastewater during treatment at treatment plants attracts attention – by an average of 25% causing a big interest. This indicates that the wastewater during treatment at the treatment plant passes through areas where sulfate reduction occurs, forming hydrogen sulfide, as well as its partial oxidation to elemental sulfur. Sulfur precipitated not only on the walls of structures, but also on activated sludge, as evidenced by its whitish color during bulking, very rapid decay and chemical analysis data.

The formation of hydrogen sulfide in wastewater by sulfate reduction during transportation of wastewater by networks or during sedimentation in biological treatment plants (including secondary clarifiers) is facilitated by a number of parameters: low redox potential, low water stability (high content of organic substances in the absence of nitrites and nitrates), the presence of specific organic substrates. The presence of hydrogen sulfide, which leads to the active development of Type 021 N and an increase of the sludge volume index, can inhibit the activity of nitrifying bacteria in activated sludge in biological wastewater treatment and the formation of nitrates. The conducted studies confirmed this assumption (figure 2). As can be seen, the lower the sludge index, the higher the content of nitrates – nitrification products in the treated



1 Hydrogen sulfide (sulfides), mg/dm^3
2 Sludge volume index, cm^3/g

Figure 1. Correlation of the sludge volume index in the aeration tank with the concentration of sulfides in the incoming wastewater.



1 Concentration of NO_3^-, mg/dm^3
2 Sludge volume index, cm^3/g

Figure 2. Nitrate concentration in treated wastewater and sludge volume index for the observation period.

wastewater.

Theoretically, an effective method for suppressing the development of sulfur filamentous bacteria Type 021N is the removal of hydrogen sulfide, a specific substrate for their development, from wastewater. Such removal can be carried out chemically during the precipitation of sulfides and by blowing off and oxidizing hydrogen sulfide with air as well. Since the concentration of hydrogen sulfide in the wastewater at object 1 after sand traps and primary clarifiers slightly increased, it is more expedient to place the operation of stripping and oxidizing hydrogen sulfide in wastewater with air directly in front of the aeration tank. This solution was implemented in the form of a pre-aerator, in which the wastewater was subjected to intensive aeration for 10 minutes. The concentration of hydrogen sulfide in wastewater entering the line of aeration tanks decreased to 0.4-0.6 mg/dm^3. This turned out to be sufficient so that, despite the high water temperature (23 °C), the sludge volume index in the entire system of wastewater treatment plants decreased from 280 to 150 cm^3/g in 2 days.

Object 2 is the local biological treatment plant (SBR reactor) of a milk processing enterprise. Sulfur compounds and thermals are typical of dairy wastewater, since sulfur is found in milk protein and in the free amino acids formed during the hydrolysis of milk protein. In addition, lactic acid is an optimal organic substrate for microbiological sulphate reduction generating hydrogen sulfide. The presence of these two factors creates an increased risk of sludge bulking at the treatment plants of milk processing enterprises, which is also noted in the statistics of activated sludge bulking made by Eikelboom [15]. In the provided samples of activated sludge from object 2, a deep violation of the technological properties of activated sludge was noted: a weakening of the compactness of flocs, its structure and shape, an increase in the sludge volume index. But the most important thing in activated sludge was found to be a mass development of filamentous bacteria (filamentous index 4-5), which, upon detailed examination, were identified as Type 021N [1, 2].

To restore the sedimentation properties of activated sludge, measures were taken to eliminate the stagnation zones of wastewater, in which sulfate reduction processes most likely developed. The measures taken to thoroughly clean the wells and the capacity of the sewage pumping station led to positive results. After 15 days, the microbiological characteristics of the sludge, the technological parameters of activated sludge flocs have changed for the better. The activated sludge filament index decreased from 5 to 3, the activated sludge flocs quality (size, shape, strength, structure) improved significantly. Thus, the removal of hydrogen sulfide from the activated sludge treatment medium is an effective intervention for suppressing the development of Type 021N filamentous bacteria and the activated sludge bulking caused by them.

4. Conclusion

Experimental research at existing sewage treatment plants in which bulking of activated sludge took place were aimed at identifying the filamentous bacteria that cause bulking and the reasons for their massive development, determining the impact of this process on the efficiency of wastewater treatment, and approving measures to suppress this process and further prevent it.

Experimental research with the help of tests recommended by Eikelbub and the identification keys developed by him allowed to identify the filamentous bacterium that caused the bulking of activated sludge in the studied municipal and local industrial treatment plants as Type 021N.

Experimental studies established a negative effect of bulking of activated sludge on the activity of nitrification in the structure, which caused a decrease in the formation of nitrates.

To suppress the bulking of activated sludge, two methods of suppressing the inflow of hydrogen sulfide into biological treatment plants were tested: blowing hydrogen sulfide from wastewater at municipal treatment plants and inhibiting its formation at local treatment plants in the precipitation and laminar flow zones. The implemented measures gave a positive result: the sludge volume index decreased to normative values, the technological properties of activated sludge flocs were restored, and the concentration of filamentous bacteria Type 021N decreased to the required minimum.

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References

[1] State of Maine Department of Environmental Protection 2009 Notes on activated sludge process control URL https://www.academia.edu/26180369/NOTES_ON_ACTIVATED_SLUDGE_PROCESS_CONTROL

[2] Sam T, Le Roes-Hill M, Hoosain N and Welz P J 2022 *Water* **14**(20) 3223 ISSN 2073-4441 URL https://doi.org/10.3390/w14203223

[3] Hashimoto K, Matsuda M, Inoue D and Ike M 2014 *Journal of Bioscience and Bioengineering* **118**(1) 64–71 ISSN 1389-1723 URL https://doi.org/10.1016/j.jbiosc.2013.12.008

[4] Guo F and Zhang T 2012 *Water Research* **46**(8) 2772–2782 ISSN 0043-1354 URL https://doi.org/10.1016/j.watres.2012.02.039

[5] Miłobędzka A, Witeska A and Muszyński A 2015 *Water Science and Technology* **73**(4) 790–797 ISSN 0273-1223 URL https://doi.org/10.2166/wst.2015.541

[6] Araújo dos Santos L, Ferreira V, Neto M M, Pereira M A, Mota M and Nicolau A 2015 *Applied Microbiology and Biotechnology* **99**(12) 5307–5316 ISSN 1432-0614 URL https://doi.org/10.1007/s00253-015-6393-8

[7] Fourest E, Craperi D, Deschamps-Roupert C, Pisicchio J L and Lenon G 2004 *Water Science and Technology* **50**(3) 29–37 ISSN 0273-1223 URL https://doi.org/10.2166/wst.2004.0157

[8] Pedro Martins A M 2004 *Bulking sludge control: kinetics, substrate storage, and process design aspects* Ph.D. thesis Delft University of Technology URL http://resolver.tudelft.nl/uuid:b0cf9088-57b2-4f35-a3da-3b94c37a64e2

[9] Ai S, Du L, Wang Z, Shao L, Kang H, Wang F and DBian 2021 *E3S Web of Conferences* **261** 04031 URL https://doi.org/10.1051/e3sconf/202126104031

[10] Henriet O, Meunier C, Henry P and Mahillon J 2017 *Scientific Reports* **7**(1) 1430 ISSN 2045-2322 URL https://doi.org/10.1038/s41598-017-01481-1

[11] Burger W, Krysiak-Baltyn K, Scales P J, Martin G J, Stickland A D and Gras S L 2017 *Water Research* **123** 578–585 ISSN 0043-1354 URL https://doi.org/10.1016/j.watres.2017.06.063

[12] Shi H X, Wang J, Liu S Y, Guo J S, Fang F, Chen Y P and Yan P 2022 *Water Research* **212** 118096 ISSN 0043-1354 URL https://doi.org/10.1016/j.watres.2022.118096

[13] Wanner J 1994 *Activated Sludge: Bulking and Foaming Control* (Boca Ration: CRC Press)

[14] Iurchenko V, Tsytlishvili K and Malovanyy M 2022 *Ecological Questions* **33**(2) 21–30 URL https://doi.org/10.12775/EQ.2022.017

[15] Eikelboom D H 2000 *Process Control of Activated Sludge Plants by Microscopic Investigation* (London: IWA Publishing) URL http://library.oapen.org/handle/20.500.12657/30982

[16] Zhmur N S 2003 *Technological and biochemical processes of wastewater treatment at facilities with aerotanks* (Moscow: AQUAROS)

[17] Guida M, Cesàro G, Lipardi I and Melluso G 2002 *Water Science and Technology* **46**(1-2) 507–510 ISSN 0273-1223 URL https://doi.org/10.2166/wst.2002.0526

[18] Duine A and Kunst S 2002 *Water Science and Technology* **46**(1-2) 29–33 ISSN 0273-1223 URL https://doi.org/10.2166/wst.2002.0451

[19] Shchetinin A I, Yurchenko V A, Malbiev B Y, Mikhnev A N, Melnik V A *et al.* 2006 *Journal of Water Chemistry and Technology* **259**(4) 83–88

[20] Netrusov A I, Egorova M A and Zakharchuk L M 2005 *Workshop on microbiology* (Moscow: Academy)

[21] List of methods for performing measurements (determinations) of the composition and properties of samples of environmental objects, emissions, wastes and discharges provisionally allowed for use by the State Inspectorate of Ukraine, approved by the Head of the State Environmental Inspectorate of Ukraine 2013

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Assessment of the hydrogeological and ameliorative state of the Kilchen irrigation system territory

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Abstract. Climatic changes, physical and moral deterioration of the main funds of land reclamation systems in Ukraine prompt a change in conceptual approaches and reform of the water management system for efficient use of irrigated lands. One of the components of the agricultural hydrotechnical reclamation development is the provision of an appropriate level of ecological and reclamation status of irrigated lands and territories adjacent to irrigation systems (first of all, an open network of canals). The purpose of these studies is to assess the modern technical and hydrogeological-ameliorative state of the Kilchen irrigation system (total area of 35.3 thousand hectares) for a long period of operation of more than 50 years. The main research methods were field diagnostic surveys of the technical conditions of the main structures and elements of the irrigation system (open channels in the earthen channel). The trends of changes in climatic conditions of the territory over the last decade are analyzed. Analytical processing of the stock materials data and field observations of changes in the groundwater level, its chemical composition and mineralization in 24 observation wells along the main channel was carried out. The main chemical composition of groundwater in the research area is characterized as sulfate and sodium-calcium with total mineralization in individual areas from 0.6-0.9 to 1.7-3.5 g/l. According to the known methods of R.O. Bayer and V.A. Kovda calculations of the predicted change in the level and critical depth of groundwater have been performed. The established terms of change vary between 9-11 years, provided that irrigation is intensified and the irrigation system is fully operational. Based on the forecasting results, groundwater mineralization is expected to decrease from 3.5 g/l to 2.27 g/l between 2021 and 2029. It was determined that the level of groundwater above the calculated critical levels in different years occupies from 30.7 to 51.0% of the territory in the area of operation of the Kilchen irrigation system. The reclamation state of part of the irrigated lands in 2021 with a total area of more than 13.000 ha was distributed according to the following criteria: 12.000 ha – favorable, 1.200 ha – satisfactory, about 50 ha – unsatisfactory due to the manifestation of soil salinization processes. As of 2021, of the soils on an area of about 10.000 hectares that were studied, almost 8.500 hectares of soils are non-saline, more than 1.200 hectares are slightly saline, and about 50 hectares are moderately saline. For comparison, in 2003, all soils on the same area were non-saline, which indicates the deterioration of the ecological and melioratic state of the territory and the decrease in the quality of irrigation water.

1. Relevance

One of the most important issues of Ukraine's national security during the war is ensuring food security [1]. Nowadays, the agrarian sector of the economy has the most dynamic development and provides a significant share of currency inflows to Ukraine. With rapid changes in climatic conditions and a shortage of soil moisture, obtaining consistently high yields of agricultural crops, regardless of weather conditions, is ensured by irrigation. Almost all irrigation systems in Ukraine were built in the 60s and 70s of the last century. The terms of their technical operation have exceeded (or are approaching) the project indicators. Among the main factors that negatively affect the operation of hydromelioration systems, the following are distinguished: inadequate state funding, which does not provide the opportunity to carry out current and capital repairs in a high-quality and timely manner; physical wear and tear of fixed assets; significant non-productive losses of water from the irrigation network, causing flooding or inundation of adjacent territories, soil salinization, etc.; the high cost of irrigation water and the use of low-quality water resources [2].

The consequence of long-term operation of hydromelioration systems at an unsatisfactory and insufficient level of technical operation is the deterioration of the ecological and meliorational state of the territories adjacent to these systems. This problem requires the development of appropriate technical and technological solutions for the further development of irrigation reclamation in Ukraine [3]. It should be noted that the priority areas of development indicated in the "Strategy of Irrigation and Drainage in Ukraine for the period until 2030" approved by the order of the Cabinet of Ministers of Ukraine No.688 dated August 14, 2019 are:

- conducting a detailed audit of the use of reclaimed land and inventory of land reclamation systems;
- implementation of institutional reforms of shade resource management and land reclamation;
- creation of the umbrella organization for effective management and reliable operation of reclamation systems;
- implementation of investment and infrastructure projects for the restoration and development of land reclamation in Ukraine.

At the same time, in order to realize the set goals, it is necessary to carry out a thorough assessment of the current state of both the technical resources of the country's reclamation complex as a whole, and the ecological and reclamation state of the territories adjacent to the irrigated systems in particular [4]. In domestic and international practice, the importance of systematic long-term data collection on the level of groundwater on irrigated lands is noted [5]. Such data are critical to research and solve many of the complex environmental problems of adjacent irrigated areas that irrigated agriculture commonly faces. Foreign researchers pay great attention to the periodicity of observing the ecological and meliorational state of irrigated lands [6] and establishing the impact of irrigation systems on the state of the surrounding natural environment [7].

At responsible facilities, hydrographs are most often used, which record data continuously, since periodic monitoring may not reflect short-term loads in the form of extreme fluctuations in water levels in hydraulic reactions. The disadvantage of constant monitoring is the need for large capital investments. However, it does not always provide an opportunity to see a global change in the trend of the groundwater level. Most often, observations are analyzed every 5-10 years.

Recently, the ecological and reclamation state of irrigated lands is affected not only by their technical condition, but also by changes in climatic indicators. The global trend of increasing air temperature during the growing season and decreasing the amount of productive precipitation leads to a greater manifestation of the salinization and salting processes of irrigated soils [8]. Climate change leads to a decrease in productive moisture in the soil and a decrease in the level of groundwater due to the lack of seasonal replenishment. Due to the lack of productive precipitation, some European countries, in particular France, state an active reduction of the aquifer and a decrease in the level of groundwater. According to the regulations in Ukraine, irrigation systems monitor the condition of irrigated and adjacent lands according to hydrogeological indicators; monitor indicators of the soils and groundwater chemical composition, the technical condition of the reclamation system, flooding of nearby settlements within the area of the reclamation system operation etc. [9].

Such monitoring of reclaimed land is carried out with the aim of ensuring rational use of land and water resources, identifying the causes of their unsatisfactory state, quality and pollution, timely implementation of reclamation measures to prevent soil degradation and harmful effects of water, reproduction of soil fertility, protection of water and land from pollution, timely performance of repair and restoration works (reconstruction) [10].

State programs are relevant and necessary to ensure the collection of data for ecological and remedial monitoring and the future forecast of the negative consequences of the impact on the environment. These programs make it possible to efficiently use the network of observation wells and monitor the water level in them at the local, regional, and state levels. Monitoring the level of groundwater on irrigated areas is an important task in the organization and implementation of ecological and remedial monitoring. Thus, the purpose of this work is to assess the hydrogeological and reclamation state of the territory in the zone of the Kilchen irrigation system influence at the current stage of exploitation.

2. Research methods

Field diagnostic surveys of the technical condition of the irrigation system's main structures and elements (open channels in the earthen channel) were carried out. Analytical processing of data from stock materials and field observations of changes in the level of groundwater and its quality in observation wells was performed. The calculation of the forecast change in the level of the groundwater critical depth was carried out using various methods (according to the methods of R. O. Bayer and V. A. Kovda). QGIS, AutoCAD, and Microsoft Excel software packages were used during the processing of the material.

3. Results and discussion

The Kilchen (formerly Frunzen) irrigation system is located on the territory of the Dnipropetrovsk region. The irrigation system was built in two phases: the first was put into operation in 1970, and the second in 1975. The total area of the irrigation area is 35.3 thousand hectares (20.1 thousand hectares and 15.2 thousand hectares, respectively). The source of power for the Kilchen irrigation system is the Dnipro Reservoir on the Samara River, from which water flows through a 4.25 km long canal by gravity to the main pumping station No. 1 (MPS-1) and is fed into the main canal of the first line (26.8 km long). The channel of the underwater channel is earthen, and the channel itself is designed for the passage of water up to 20 m^3/s.

Main and distribution canals (total length 47 km) of the Kilchen irrigation system are built with an anti-filtration coating mainly from reinforced concrete slabs laid on polyethylene film, as well as in open reinforced concrete trays (5.2 km long).

The drainage network was built on an area of 24.6 thousand hectares, which makes it possible to maintain an optimal water-salt regime in the irrigated and adjacent territories. A cut-off horizontal drainage (3.6 km long) was created along the main canal of the first stage, and forest strips were planted along the borders of the fields. The first stage of the Kilchen irrigation array is located on the left bank of the Dnipro River within the Dnipro and Tsarychan districts of the Dnipropetrovsk region (figure 1).

The irrigation array is located mainly on the second floodplain terrace of the Dnipro and partially on the watershed plateau of the Kilchen and Chaplinka rivers. The surface is flat, dissected by a truss-beam network. Soils are not saline. The soil cover consists mainly of ordinary low- and medium-humus rich chernozems. Hydrogeological conditions are marked by the presence of an aquifer in anthropogenic sediments at a depth of 2-15 m, on the watershed

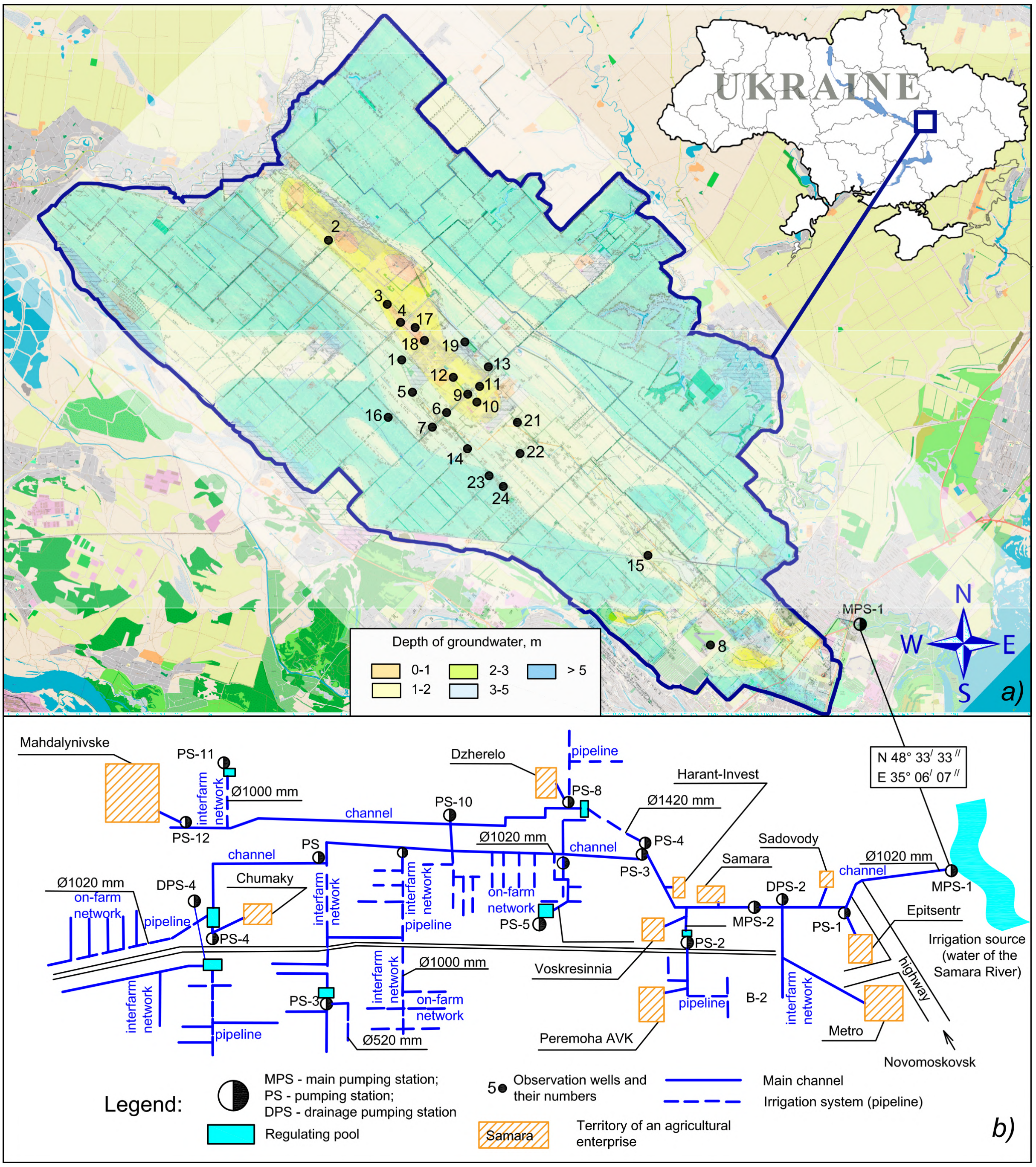

Figure 1. Overview diagram of the Kilchen irrigation system: a) – an area within the region with specific levels of groundwater; b) – a diagram indicating the positions of channels and pumping stations.

plateau – up to 45 m. The chemical composition of groundwater is sulfate and sodium-calcium with mineralization from 0.6-0.9 to 1.7-3.5 g/l.

The northern border of the irrigation system runs along the main channel and along the village of Ulyanivka to the Chaplinka River, and the western part of the massif is limited to the village of Petrikyvka. The southern border runs along the Dnipro-Poltava highway, and the eastern border along the Dnipro-Novomoskovsk highway. The total length of the irrigated massif is 35 km with a width of 7-9 km.

(a)

(b)

Figure 2. Anti-filtration lining of the main channel with reinforced concrete slabs: (*a*) – at the construction stage in 1965 (archival photo); (*b*) – unsatisfactory technical condition and damage at the current level of operation (author's photo).

The natural boundaries of the irrigation array are: in the north – the slopes of the watershed plateau, in the south – the ledge of the first floodplain terrace of the Dnipro River, in the east – the Kilchen River and in the west – the Chaplinka River. Next to the irrigation network, there are 53 agricultural enterprises with a total area of about 13.331 hectares, including 1.790 hectares of irrigated land. Agricultural enterprises specialize in the production of grain and vegetable and meat and dairy products.

As of April 1, 2021, the irrigated area under the control of the Kilchen irrigation system in the Dnipro district is 96,601 hectares, including 1,549 hectares of actually irrigated land.

According to the results, own field diagnostic surveys of the main channel testify to its unsatisfactory technical condition at the current level of operation (figure 2). In particular, the damage to the anti-filtration coating of the canal, the development of shrubby vegetation, and the destruction of individual water supply and water permeable elements of the structure are noted.

The effectiveness of irrigation hydrotechnical reclamations and the quality of surface and groundwater are impacted by rapid changes in climate. The climatic conditions in 2010 and 2018 showed an increase in air temperature by 1.97 °C and 0.84 °C compared to the long-term average temperature of 9.2 °C (table 1). However, in 2021, the average annual air temperature was almost similar to the long-term values. In 2010, the amount of precipitation was 13.3 mm higher than the long-term average value of 429 mm, while in 2018 and 2021, the precipitation levels exceeded the long-term average by 255.7 mm and 252 mm, respectively. Data on meteorological observations from previous years were obtained from open sources on the internet and archives of the Dnipropetrovsk Hydrogeological and Reclamation Expedition.

The assessment of the hydrogeological and reclamation state of irrigated lands was carried out based on the analysis of the groundwater level depth during the vegetation and irrigation period of the corresponding year. On the area of the irrigation array, the regime network consists of 255 observation wells.

In 2021, the distribution of controlled areas according to the depth of groundwater levels of 2-3 m on the irrigation array was 302 hectares, with a level of 3-5 m – more than 4 thousand hectares, and with a level of more than 5 m – about 9 thousand hectares. The level of groundwater in some observation wells by years of research is shown in figure 3.

Table 1. Dynamics of changes in climatic indicators at the object of research.

Month	Average air temperature, °C			Precipitation, mm		
	Year			Year		
	2010	2018	2021	2010	2018	2021
January	-1.00	-2.9	-2.0	0.2	72.6	57.9
February	0.20	-2.6	-3.8	0.2	46.2	53.5
March	2.00	-1.5	1.6	17.5	144.9	49
April	10.5	12.9	8.0	19.9	16.9	54.4
May	17.4	18.9	15.8	67.6	31.5	27.9
June	22.7	21.7	19.5	48.9	53.0	202.5
July	24.8	22.5	23.6	70.3	79.3	70.8
August	25.8	23.4	22.8	11.2	0.0	51.1
September	16.9	17.8	13.8	55.8	74.4	23.9
October	6.4	11.5	8.4	53.4	22.8	2.2
November	8.8	0.6	4.3	38.1	37.4	38.2
December	-0.5	-1.8	-0.9	59.2	105.7	49.6

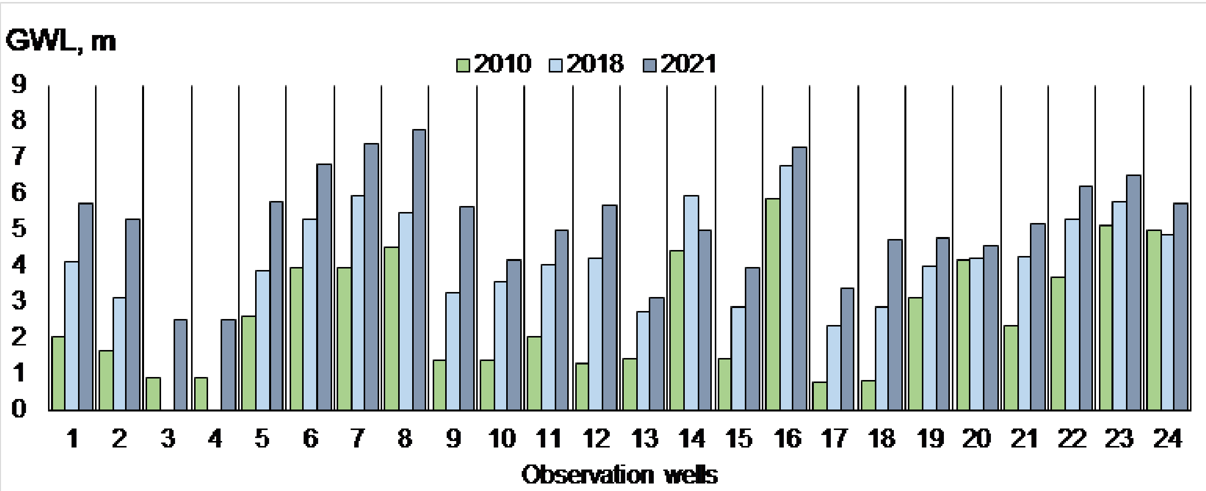

Figure 3. Groundwater level (GWL) in the area of operation of the Kilchen irrigation system main canal (average annual data).

In order to assess the hydrogeological and meliorational state of the sites in relation to the depth of the subsoil, it is necessary to determine their critical depth of the subsoil. The critical depth of the groundwater level is determined by two methods: according to the R. O. Bayer's method – determined by mineralization and the type of the groundwater chemical composition [11]; according to the V. A. Kovda's method [12] – calculated using the formula:

$$H_{kr} = 170 + 8 \cdot t\,(cm)\,, \tag{1}$$

where t – is the average annual air temperature.

According to the R. O. Bayer's method, with a sulfate type of soil and mineralization of groundwater up to 3 g/l, the maximum value of the groundwater critical level occurrence is 1.5 m.

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The average annual air temperature for the Dnipro region is 9.2 °C, therefore according to the formula of V. A. Kovda, the maximum value of the critical level of groundwater is: $H_{kr} = 170 + 8 \cdot 9.2 = 2.4\,(\mathrm{m})$.

In 2010, with the lowest amount of precipitation and the highest average air temperature according to average annual indicators, an unsatisfactory hydrogeological and reclamation condition was observed in the territory of the irrigation system. The level of groundwater above the critical level (2.4 m) occupied 51% of the territory around operation of the Kilchen irrigation system, of which 30.7% exceeded the critical depth of the groundwater level above 1.5 m. The rise in the level of groundwater led to flooding of the territories of the Ulyanivka village and the Chumaki village and the rise of the water level in Lake "Ozerishche", which caused the basements of buildings in these settlements to be filled with water. There was a pull-up of salts from mineralized groundwater in these territories, which prompted the processes of salinization and salinization.

Areas with an unsatisfactory hydrogeological-ameliorative state of irrigated lands include areas with a depth of GWL above the critical level for their mineralization of more than 1 g/l, and areas with an average degree of salinity or an average degree of soil salinity.

Areas with a satisfactory hydrogeological and meliorational condition of irrigated lands include areas with a depth of GWL from critical to 5 m with mineralization of more than 1 g/l, and areas with a weak degree of salinity or a weak degree of soil salinity.

Areas with a good hydrogeological and meliorational condition of the land include areas with a depth of groundwater level above the critical level with good natural or artificial drainage and fresh water, as well as areas with non-saline and non-saline lands.

In 2010, 42% of the territory was in an unsatisfactory reclamation state due to the high level of groundwater (above 1.5 m) and the establishment of an average degree of salinity on an area of 52 hectares, while in 2018 and 2021, the ecological and reclamation state changed significantly towards improvement. Climatic indicators during this period were characterized by a slight increase in the average annual air temperature and a significant increase in the amount of precipitation – by 58-60% of the average long-term values. The specified amount of precipitation was extremely unevenly distributed throughout the year and was showery in nature. Despite the increased amount of atmospheric precipitation at that time, the stabilization of GWL was noted due to their redistribution over the surface by horizontal spreading and weathering.

In 2018 and 2021, a decrease in the groundwater level was observed in all observation wells. The terrain in the area of observation well 18 is of concern. The rate of groundwater level rise per year is 0.3 m. It was necessary to calculate the time of groundwater rise to the critical level. If such a trend is maintained, the time for the groundwater level to rise to critical values is determined by the formula:

$$t = \frac{Hp - Hkr}{\triangle h}, \tag{2}$$

where H_p – groundwater level before irrigation; H_{kr} – critical depth of the groundwater level, m; $\triangle h$ – the amount of groundwater level rise per year, m.

The time for groundwater to rise from the level of 5 m according to formula (2) to the critical level of 1.5 m is 11 years and 7 months, and the rise to the level of 2.4 m is 8 years and 8 months (figure 4).

Predicting the mineralization level of groundwater when it reaches the critical depth is achievable by determining the average mineralization of the water layer upon reaching a certain level of groundwater [13]. This calculation depends on the infiltration of irrigation water and atmospheric precipitation as per the formula

$$C = \frac{C_0 \cdot h_0 + C_n \cdot h_n}{h}, \mathrm{g/l} \tag{3}$$

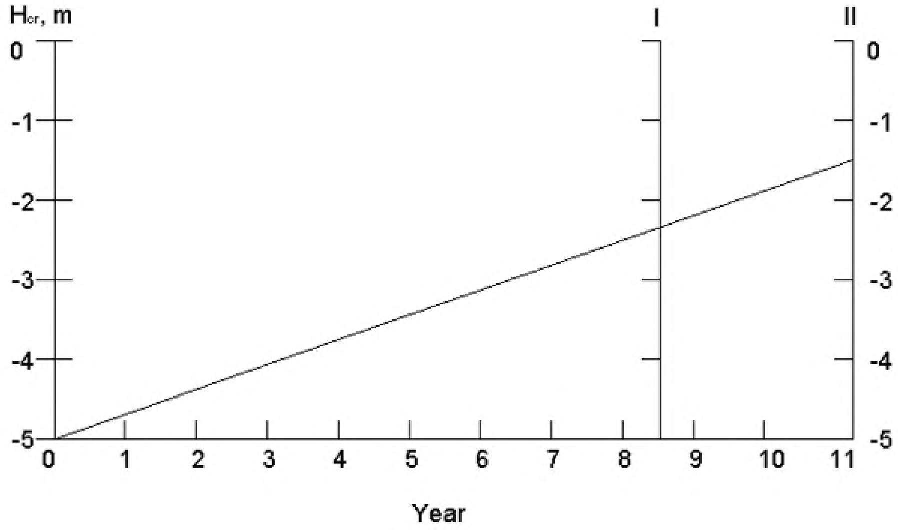

Figure 4. The time prediction of reaching the critical level of groundwater at observation well 14.

where C – average mineralization of the groundwater layer, g/l; C_0 – mineralization of the water infiltration layer, g/l; h_0 – layer of the infiltration water, m; C_n – mineralization of the solution in the pores squeezed out of the aeration zone, g/l; h_n – a layer of natural moisture squeezed out of the aeration zone, m; h – the height of the groundwater level rise during the t period, m.

The mineralization of the water infiltration layer is determined by the formula

$$C = \frac{N_{precp} \cdot M_{precp} + N_{irr} \cdot M_{irr}}{N_{precp} + Nirr}, \text{g/l} \tag{4}$$

where N_{precp} – the total rate of atmospheric precipitation for the t period, m^3/ha; M_{precp} – mineralization of precipitation, g/l; N_{irr} – total irrigation rate for t period, m^3/ha; M_{irr} – mineralization of irrigation water, g/l.

The mineralization of the solution in the pores, squeezed out of the aeration zone, is determined as follows

$$C_n = \frac{C_a \cdot 1000}{W \cdot Wg}, \text{g/l} \tag{5}$$

where C_a – the average content of salts in the soils of the aeration zone, %; 1000 – conversion factor; W – relative humidity of the soil, %; W_g – hygroscopic soil moisture, %.

The typical water mineralization for the Kilchen irrigation system is 2.31 g/l. In 2021, based on climatic indicators, the total atmospheric precipitation rate was 6810 m^3/ha with a mineralization level of 0.02 g/l. "Agro-Kompaniya" LLC requires a total irrigation rate of 13,650 m^3/ha, resulting in a mineralization of the infiltration layer of water at 1.55 g/l. The relative humidity of the soil for Agro-Company LLC ranges between 24-26 %, with hygroscopic humidity at 5 % and an average salt content of 0.24 %, leading to a mineralization of the solution in the pores squeezed out of the aeration zone at 2 g/l. The predicted mineralization for a 2.1 m layer of infiltration water and a 1.1 m layer of natural moisture squeezed out of the aeration zone at a groundwater level rise of 2.4 m is 2.27 g/l. As a result, the mineralization of groundwater is expected to decrease from 3.5 g/l to 2.27 g/l between 2021 to 2029.

The meliorative state of irrigated lands in 2021 with a total area of more than 13,000 hectares is divided according to the relevant criteria into 12.000 hectares – favorable, 1.200 hectares – satisfactory, about 50 hectares – unsatisfactory due to the manifestation of salinization processes.

As of spring 2021, out of the 9.683 ha of soils studied, 8.409 ha are non-saline, 1.236 ha are slightly saline, and 38 ha are moderately saline, while all soils were non-saline in the same area in 2003.

The following studies of the ecological and reclamation state of the Kielce irrigation system in 2021 showed the processes of the groundwater level stabilization and the absence of a systematic rise of it to a critical level compared to what was observed in 2010. It is necessary to pay attention to the territory with an underground water level of 2-3 m (302 hectares of area) and land in LLC "Agro-Kompaniya", where no general tendency to decrease the underground water level was observed.

4. Conclusions

In order to improve the ecological and remedial the soils condition of the Kilchen irrigation system, it is proposed to carry out systematic control of the groundwater level. Increased attention should be paid to monitoring the observation well 14, which is located on the lands of Agro-Company LLC. On irrigated areas, it is necessary to control the irrigation regime of agricultural crops in accordance with the groundwater level in those places where it reaches the level of 2-3 m, and to maintain the humidity of the soil arable layer at the level of 80-85% the lowest moisture content of the soil. It is recommended to carry out chemical reclamation measures on saline areas by applying phosphogypsum at the rate of 3 t/ha under plowing in the fall once every 3 years.

It is worth noting that over the last decade, the groundwater level in the area of operation of the Kilchen irrigation system has decreased significantly. The main reasons for this are a change in climatic conditions with a tendency towards dryness, as well as a decrease in water consumption. Nowadays, several times less water resources are pumped through the main channel than is provided by its design indicators.

The calculated critical depth of the groundwater level according to the method of R. O. Bayer is 1.5 m, and according to V. A. Kovda – 2.4 m. The estimated time to reach the critical level of groundwater is about 9-11 years. Taking into account the constant decrease in water consumption volumes, this indicator can be significantly reduced for a period of more than 20 years. The main chemical composition of groundwater is characterized as sulfate and sodium-calcium with total mineralization in some areas from 0.6-0.9 to 1.7-3.5 g/l. Based on the forecasting results, groundwater mineralization is expected to decrease from 3.5 g/l to 2.27 g/l between 2021 and 2029.

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References

[1] Hadzalo Y M, Ibatullin I I and Luzan Y Y 2022 *Bulletin of Agricultural Science* **100**(8) 5–15 ISSN 2308-9377 URL `https://doi.org/10.31073/agrovisnyk202208-01`

[2] Baliuk S A, Romashchenko M I and Truskavetskyi R S 2018 *AgroChemistry and Soil Science* (87) 5–10 ISSN 05872596, 26166852 URL `https://doi.org/10.31073/acss87-01`

[3] Romaschenko M, Tarariko J, Shatkovs'kyj A, Sajdak R and Soroka J 2015 *Bulletin of Agricultural Science* **93**(10) 5–9 ISSN 2308-9377 URL `https://doi.org/10.31073/agrovisnyk201510-01`

[4] Baliuk S A, Romashchenko M I and Stashuk V A 2009 *Naukovi osnovy okhorony i ratsionalnoho vykorystannia zroshuvanykh zemel Ukrainy* (Kyiv: Ahrarna nauka) ISBN 978-966-540-289-3

[5] Taylor C J and Alley W M 2001 Ground-Water-Level Monitoring and the Importance of Long-Term Water-Level Data U.S. Geological Circular 1217 U.S. Department of the Interior U.S. Geological Survey Denver, Colorado URL https://pubs.usgs.gov/circ/circ1217/

[6] Peck A J 1978 *Soil Research* **16**(2) 157–168 ISSN 1838-6768 URL https://doi.org/10.1071/sr9780157

[7] Rengasamy P *Journal of Experimental Botany* **57**(5) 1017–1023 ISSN 0022-0957 URL https://doi.org/10.1093/jxb/erj108

[8] Singh A 2021 *Journal of Environmental Management* **277** 111383 ISSN 0301-4797 URL https://doi.org/10.1016/j.jenvman.2020.111383

[9] Makarova T, Domaratskiy G, Hapich Y and O K 2021 *Indian Journal of Ecology* **48** 789–795 ISSN 0304-5250 URL https://www.indianjournals.com/ijor.aspx?target=ijor:ije1&volume=48&issue=3&article=028

[10] Orlinska O, Pikarenia D and Chushkina I 2022 *AIP Conference Proceedings* **2676**(1) ISSN 0094-243X URL https://doi.org/10.1063/5.0109330

[11] Bayer R O 1973 *Peculiarities of formation of hydrogeological and reclamation conditions on irrigated lands in the south of Ukraine* (Znannia)

[12] Kovda V A 1979 *Climatic Change* **2**(2) 103–108 ISSN 1573-1480 URL https://doi.org/10.1007/BF00133217

[13] Gadzalo Y, Romashchenko M and Yatsiuk M 2018 *Proceedings of IAHS* **376** 63–68 ISSN 2199-8981 URL https://doi.org/10.5194/piahs-376-63-2018

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Sustainable processing of lignocellulosic biomass

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Abstract. Biomass gasification is one of the effective methods of obtaining electrical and thermal energy. Thermal gasification is a simple and effective method for most lignocellulosic waste. The generation of combustible gases under such conditions has significant prospects both in the national economy and in a number of chemical-technological processes. The high-ash carbon residue remaining after thermolysis has shown its effectiveness as one of the important components of organo-mineral fertilizers. The results of field research in 2018-2019 with Moskito corn hybrid (*Zea mays L.*) and Mulan winter wheat F2 hybrid (*Triticum aestivum L.*) on dark-gray podzolic soil confirmed the high agrochemical efficiency of our proposed fertilizers. The introduction of Moskito corn hybrid organo-mineral fertilizer into the nutrition system improved the structural indicators of the harvest: in the experiment, the 1000 grains weight increased by 14.7%, the mass of grain from one cob – by 20% compared to the control. Balanced nutrition of experimental plants Mulan winter wheat F2 hybrid in the variant with the use of BG-II when sowing at a dose of 1t/ha and favourable weather conditions led to an increase in grain quality (protein content) to the 2nd class – 13.0% against the 3rd grade in control (12.2%).

1. Introduction

The constant increase in the price of energy resources and the annual decrease in their reserves prompts the scientific community to search for and develop alternative energy sources [1–3]. Today, technology using biomass as a renewable source is gaining significant development. The generation of combustible gases from organic waste has significant prospects both in the national economy and in some chemical-technological processes [4–12]. Thus, the existing situation in Ukraine for the development and implementation of the concept of sustainable development implies not only the inextricable connection of its economic, ecological and social components but also their balance.

Agricultural waste, which in most cases is not used, creates a number of environmental problems or simply rots. It is clear that only the implementation of radical steps could significantly change the situation. One of these steps should be deep processing of accumulated waste, aimed not only at reducing its volume but also at maximizing the energy and resource potential of such waste. Gasification of biomass is one of the effective methods of obtaining electrical and thermal energy [4–12]. The attractiveness of using vegetable raw materials is the absence of sulfur-containing compounds, and as a result of high-temperature thermal decomposition, it is possible to obtain combustible gas, which does not produce dangerous oxides in the environment when burned. Thermal gasification is a simple and effective method for most cellulose- and lignin-containing biomass waste. Reviews of research, demonstration and commercial biomass gasification plants that exist in the world are given in works [13–17]. A byproduct of gasification is an ash residue [18–20]. The processing of waste generated by society is one of the indicators of its sustainability [21, 22]. Therefore, in most of the developed countries utilisation and wastes disposal have become a priority in the economic sectors. In today's high-tech economy, innovative products that are made from waste from industrial processing of lignocellulosic biomass are becoming more and more important [20–22]. Such innovations should become the basis of ensuring advanced positions in the production of organic-mineral fertilizers field, and fodder, which are aimed at technological and organizational modernization and competitiveness. At the current level of development of science and technology, it is optimal to use secondary raw materials. In addition, 800-900 thousand tons of limestone and granulated organic-mineral fertilizers and other products can be produced annually from unused processing waste [20, 23].

Nowadays, as a result of high prices for fertilizers, agrochemical science specialists face the problem of determining the most economically and agrochemically effective system of improvement (types of fertilizers, methods and rates of application). It should be noted that the large grounds in the country have a low supply of available phosphorus. At the same time, the main problem in agriculture remains the increase in the production of high-quality food and fodder grain [24, 25]. In corn and wheat, due to a lack of phosphorus, there is a free delay in development, the ripening period comes later, and there is a risk of under-ripening, given the rather short growing season [26]. Phosphorus is absorbed by corn approximately evenly for a long time until the harvest is reached. It is phosphorus fertilizers that stimulate the development of the root system, laying reproductive organs, contribute to the rapid formation of cobs and contribute to the achievement of the harvest. The lack of available phosphorus in plant nutrition inhibits the growth and development of flowers and grains in corn cobs. Corn has an increased need for potassium, as do other carbohydrate-rich crops [27]. It is necessary for the formation of cobs and the accumulation of starch and sugar. In addition, corn is quite sensitive to the organic fertilizers application and requires a high rate of mineral components in the fertilization system.

Taking into account modern trends, the growth of phosphorus needs in agricultural production and the lack of an opportunity to satisfy them at the expense of mineral raw materials of domestic phosphate reserves, the method of utilization of ash from the sediments of the aeration station into a valuable organic-mineral fertilizer is quite justified. XRF analysis of ash obtained during the gasification of municipal sludge showed a sufficiently high P_2O_5 content at the level of 16.4%, for comparison, superphosphate contains 19-21% P_2O_5 [28]. Ash, which is formed in this way, has the following main components: silicon dioxide, phosphates of iron, calcium, magnesium, silicates of aluminium, potassium, iron, and others. In addition, ash contains biogenic meso- and microelements (sulfur, boron, manganese, zinc, molybdenum, and others), as well as compounds in the form of main phosphates and silicates [28]. The existing reagent methods, which ensure the transformation of heavy metals into a stationary state, mostly have a temporary effect or are quite expensive. The use of products of humic nature is an effective means for their detoxification.

Thus, the aim of our work was the production of high-energy gas by gasification of lignocellulosic waste and the creation of organo-mineral fertilizers based on the ash of processed plant waste and sediments of the aeration station, the humic component and the study of their influence on the yield and quality of winter wheat and corn grains. The development of the formulation of such composite ecologically safe fertilizers of prolonged action, and their use in agricultural production will allow increasing not only the supply of phosphorus and potassium to wheat plants, but also the drought, frost, and winter resistance of the culture. All this will contribute to the improvement of the economic and ecological indicators of crop production – a reduction in the cost of wheat grain due to an increase in the yield and quality of the grain, a reduction in the costs of phosphorus and nitrogen fertilizers at a negligible cost and the cost norms of new organo-mineral fertilizers of prolonged action.

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2. Materials and methods

Air-dry switchgrass (*Panicum virgatum L.*), rice husk and pine sawdust (fraction 2-5 mm) from Kyiv's region of Ukraine with the following characteristics: humidity 9.1, 11.0, 9.5% (respectively), the proportion of inorganic components to dry weight of 3.3, 18.0, 1.2% (respectively) (table 1) and the proportion of organic components – 96.7, 82.0, 98.8% (respectively) was used.

Table 1. Oxide composition of lignocellulose biomass ash.

Elements as oxide	Content (%mass.)		
	switchgrass	rice husk	pine sawdust
MnO_2	0.091	–	5.189
SiO_2	49.048	91.953	6.264
P_2O_5	9.8138	–	9.021
SO_2	4.158	0.344	7.526
K_2O	3.184	2.342	–
CaO	25.423	1.599	57.717
Fe_2O_3	1.072	0.087	1.071
Al_2O_3	–	–	2.800
ZnO	0.137	ppm 57	0.313
CuO	0.192	ppm 14	0.463
ZrO_2	ppm 49	–	–
MgO	6.751	3.559	9.278
Ni_2O_3	ppm 43	–	–
TiO_2	0.090	–	0.359

2.1. Gasification of lignocellulose biomass

Lignocellulosic biomass gasification was carried out at the installation [29] in two modes: under conditions of incomplete oxidation of raw materials with the formation of combustible gases, air containing 21% oxygen and 78% nitrogen is used as an oxidizer, and in an inert atmosphere (argon).

2.2. Characterisation of raw materials and obtaining products

All chemical analysis was carried out twice allowing to calculate the mean values and standard deviations, which do not exceed 5%. The inorganic components were determined using Expert 3L XRF (INAM, Ukraine). The sample was analysed three times. The calorific value of the samples was investigated on an IKA C200 (Germany) calorimeter according to a standardized method, by burning the sample in an oxygen atmosphere in a calorimeter bomb. The results were determined in automatic mode on the installed software. The qualitative and quantitative composition of the formed gases and liquid products was determined by the gas chromatography method. Gas chromatographic analysis of inorganic gases (hydrogen, carbon mono- and dioxide) and methane was carried out on a chromatograph Chrom-5 (Czech Republic) with a detector for measuring the thermal conductivity of gases. For the analysis of light gases, stainless steel 1.5 m long and 3 mm internal diameter, filled with a sorbent: activated charcoal of the SKT brand with a fraction of 0.25–0.50 mm, impregnated with a 10% $NiSO_4$ solution. The carrier gas is argon, the flow rate of which was 20 ml/min. The temperature of the columns thermostat and the detector is 100 °C, the evaporator temperature – 120 °C, and the detector current – 40 mA.

Hydrogen analysis was carried out on a glass chromatographic column with a length of 1.5 m and an internal diameter of 3 mm, filled with pre-fired CaA zeolite with a fraction of 0.25–0.50 mm. The carrier gas is argon, the flow rate of which was 30 ml/min. Analysis temperature – 60 °C, evaporator temperature – 120 °C, detector current – 80 mA. The gas sample was introduced into the chromatographic column through a calibrated loop using a dosing tap. The sample volume was 0.37 ml. Analysis of organic reaction products was carried out on a chromatograph "Agilent Technologies 7890A" (Agilent, USA) which was equipped with a flame ionization detector and using a DB-624 UI quartz capillary column with a length of 60 m and an internal diameter of 0.32 mm in a combined temperature regime (isothermal – 10 minutes at 40 °C, then programming the temperature from 40 to 250 °C at a speed of 5 degrees/min. Samples were introduced into the column with a microsyringe with a capacity of 1.0 mcl. Processing of the analysis results was carried out according to the areas of chromatographic peaks by the method of internal normalization using calibration coefficients.

2.3. Field experiments of organo-mineral fertilizers

To carry out scientific research work on determining the efficiency of using organo-mineral fertilizers based on the ash of plant waste and sediments of the aeration station in feeding Moskito corn hybrid (*Zea mays L.*) and Mulan winter wheat F2 hybrid (*Triticum aestivum L*) the following were used:

- ash from the Bortnychi wastewater treatment plant sludge with contents: P_2O_5 – 16.4 %, CaO – 6 %, Al_2O_3 – 10%, SiO_2 – 56 %, less than 1% – oxides Cu, Fe, Zn, Ti, S, Mn and Ni;
- rice husk ash with amorphous SiO_2 content – 97.8 % and close to 1 % K_2O and CaO;
- sunflower husk ash with K_2O content – 58%;
- urea;
- humic component – potassium lignohumate grade A, TU 2431-007-31054001-99 – a mixture of potassium salts of humic and fulvic acids, macro- and microelements (S, Ca, Si and others) has the properties of an adaptogen, immunomodulator, adhesive.

Field experiments was carried out in the experimental field in the Horodyzhe village t of Boryspil district of Kyiv region on dark gray podzolic light loam soil with average content of mobile compounds of basic macronutrients.

The first experiments with Moskito corn hybrid (*Zea mays L.*) were performed on four repetitions. The area of the sown area was 1300 m^2, the accounting area was 1200 m^2. Placement of options – systematic. Seed sowing rate – 80 thousand similar corn's seeds per ha. The predecessor in the experiment was corn. Agrotechnics is typical for the Forest-Steppe zone of the Left Bank and adapted to farm conditions. The scheme of the experiment with Moskito corn hybrid (*Zea mays L.*) provides the following doses of mineral fertilizers: before sowing was applied OMF-I at a dose of 0.5 t per ha on the background of nitroammophos fertilizer 32:32:32 (200 kg/ha) before sowing, liquid complex fertilizers (ammonium polyphosphate (APP)) ($N_{16}P_{55}$) at a dose of 150 kg/ha, urea ammonium nitrate (UAN-32) N_{96} (300 kg/ha) and timely nitrogen fertilization with ammonium sulfate (100 kg/ha) N_{21}, in certain phases of the growing season. Control – background ($N_{165}P_{87}K_{32}$), without the introduction of organic-mineral fertilizer. The main agrotechnical measure for the intensification of plant growth and development, strengthening the absorptive function of the root system, was the application of organo-mineral fertilizer at a dose of 0.5 t/ha according to the experiment scheme:

1. Background (control) – $N_{165}P_{87}K_{32}$;
2. Background + OMF-I – 0.5 t/ha.

Direct sowing of corn seeds was carried out with a Super Walter W1770 seeder. According to climatic conditions, the growing season of 2018 year was marked by variability and contrast of the first and second half of the corn growing season. The first half was characterized by waterlogging, and the second – high temperatures and heat (temperature 25-30 ^oC and above). Due to the sufficient moisture content in the soil, the corn plants grew well and developed to a state of milk-wax ripeness, in which the harvest was recorded and plant samples were taken according to the standard method – GOST-27262.

The second experiment was performed on four repetitions. The area of the sown area was 2.0 ha, the accounting area was 1.6 ha. Placement of options – systematic. The predecessor in the experiment was sunflower. According to the experiment scheme, the fertilizer application was carried out on September 25, and the sowing – was on September 28. The rate of sowing is 250 kg/ha, and the rate of new BG-II organic-mineral fertilizers application is 0.6 and 1.0 t/ha. Agrotechnics is typical for the Forest-Steppe zone of the Left Bank and adapted to farm conditions.

1. Background (control) – $N_{165}P_{87}K_{32}$.
2. Background + BG-II – 0.6 t/ha.
3. Background + BG-II – 1.0 t/ha.

The fertilization system of Mulan winter wheat F2 hybrid (*Triticum aestivum L*) provided for the introduction of 200 kg of 13:13:29 fertilizer mixes under the main tillage and 200 kg of urea-ammonia mixture after the restoration of spring vegetation in the control.

Harvesting and accounting were performed manually from each plot by the weight method according to the Dospekhov's method [30] in the phase of full grain maturity. Corn and winter wheat grain moisture and their structural analysis was carried out in cob samples (50 pcs.) and sheaves (50 pcs.), which were taken during harvesting separately at each accounting plot. Crop grain yield was calculated at a moisture content of 14%.

Plant sample selection and preparation were performed according to standard methods [31]. The content of nitrogen and phosphorus after wet ashing in dry Moskito corn hybrid (*Zea mays L.*) and Mulan winter wheat F2 hybrid (*Triticum aestivum L*) samples were determined by the method of Ginsburg with the following determination: nitrogen – photometric method using Nessler's reagent, phosphorus – photometrically by the method of Denizhe in modification of Levitsky. The inorganic components of plant sample ash were determined using Expert 3L XRF (INAM, Ukraine).

Determining the structure of the corn and winter wheat harvest was carried out by the Maysuryan method The corn and winter wheat harvest structure was carried out by the Maisuryan method, and the dry matter content of the grain was determined by the thermogravimetric method (GOST 13586.5-93), 1000 grains weight (GOST 10842-89), determination of hectolitre weight (GOST 10840-64). Determination of grain quality was performed by infrared spectroscopy Infratec 1241 (DSTU 4525:2006 and DSTU 4117-2007).

3. Results and discussion

The raw material that enters the high-temperature zone under the action of the oxidant – air decomposes and turns into gas and ash components, which in turn are carried out of the heat treatment zone into the cooling and separation zone in the separator. Ash was separated from the gas in the separator, which after passing through the cleaning line, was burned on a burner. After a certain period of time, gas was sampled for analysis. The results are shown in table 2.

From the obtained results it can be seen (table 2) that the main combustible component after gasification in the air environment is carbon monoxide, of which at least 20% is generated, the amount of hydrogen does not exceed 10%, methane 5%, C_2-C_6 hydrocarbons 2%. In turn, such

Table 2. Analysis of the generated gas.

Gas component	Content in the gas phase (%mass.)					
	rice husk		switchgrass		pine sawdust	
	air	Ar	air	Ar	air	Ar
H_2	8.90	33.45	8.55	34.47	7.55	32.54
N_2	51.45	5.02	52.24	4.63	51.00	4.26
CO	20.33	32.30	20.70	31.84	23.30	33.04
Hydrocarbons C_2-C_6	2.15	1.02	1.92	0.92	2.45	0.95
CO_2	11.14	20.08	11.53	20.46	9.70	21.23
H_2O	1.75	1.40	1.36	1.25	1.50	1.30

gas contains a non-combustible part, which consists of nitrogen – at least 50%, which is due to the nature of the oxidizer and carbon dioxide, which is about 10% in the gas. The energy characteristic of such gas is in the range of 5400-6500 kJ/m^3. At the same time, the gas produced during the process in an argon environment has a calorific value of 10,000 kJ/m^3, which does not contradict and corresponds to literature data [32]. Such gases can be used as a substitute for natural gas, with a much lower calorific value, or in electricity generating plants.

The carbon residue left after the process is a valuable raw material. Such a product from switchgrass and pine sawdust is a low-ash substance (table 3), which is important for metallurgy, where coke is used as a reducing agent. In turn, it is undesirable to obtain coke from rice husk for direct use as fuel due to the high ash content (table 3). But such material is a direct raw material for synthesising such materials as silicon carbide due to the high content of amorphous silicon dioxide – 95-96% [33], and using the previously described ecologically safe waste-free technology and highly pure biogenic silicon dioxide [34].

Table 3. Characteristics of carbon material from biomass.

Raw materials	Higher heat of combustion (J/g)	Ashiness (%)
Rice husk	18078	37.0-39.0
Pine sawdust	19055	2.0-3.0
Switchgrass	19689	6.0-8.0

In addition, such a high-ash carbon residue showed its effectiveness when using it in the production of organo-mineral fertilizers. In order to solve the optimization of phosphorus nutrition of corn on dark grey podzolized soil, OMF-II was applied to the fertilization system in a post-sowing application at a dose of 0.5 t/ha. Our structural analysis shows that all the structure elements participate in crop formation and change depending on the level of nitrogen, phosphorus, potassium, microelements and weather conditions during the growing season of the corn plants. Cob and grain sizes are important elements of crop structure that directly affect the corn plants' productivity. As evidenced by the structural analysis data (table 4), the absence of OMF in the fertilization system affected the reduction of such important indicators as the grain yield of one plant and the 1000 grains weight, which have a significant impact on the yield.

Cob diameter under the influence of fertilizer variants in the experiment increased by 12%. The largest cobs of the plant were formed with the application of 0.5 t/ha OMF-II – 20.1 cm. Quantitative analysis of such cob indicators as the number of rows and grains per row shows a significant increase in these indicators relative to control. The content of grains per row increased

Table 4. Elements of the yield structure and productivity of Moskito corn hybrid, 2018.

Treatment	Cob diameter (cm)	Cob length (cm)	Cob weight (g)	Number of rows (pcs)	The number of grains per row (pcs)	The number of grains per cob (pcs)	1000 grains weight (g)
$N_{165}P_{87}K_{32}$ – background	4.5±0.03	18.2±0.6	206±10.6	13,9±0,41	39.6±1.6	534±22.9	278±11.9
Background + OMF -II (0.5 t/ha)	4.9±0.03	20.1±0.6	219±10.5	14.3±0.43	45.0±1.6	639±30.1	319±15.3

by 13% with the introduction of OMF-II.

One of the important indicators of crop structure, which is the most prerequisite for increasing yields is grains weight, which is formed on the cob. The largest weight of grain in the cob was established – when applying OMF at a dose of 0.5 t/ha – 643g (+20%) compared to control. The 1000 grains weight, as an indicator of the grain size formed on the cobs, was the highest – 319 g in the variant where OMF was applied at a dose of 0.5 t/ha and exceeded the control indicator by 14.7%.

Corn feeding conditions for grain, soil and climatic conditions during the growing season and the method of soil cultivation largely determine the amount of its harvest. Establishing the difference between the corns yield under mineral and organo-mineral fertilization systems with the application of our fertilizers was aimed of our research. This is evidenced by the results of the study of the effect of OMF and mineral fertilizers on productivity in our experiment with corn (table 5). In our investigation, humic acids, biophilic silicon, and sulfur in the composition of OMF contribute to the mobilization of poorly soluble phosphates of fertilizers and soil and the improvement of phosphorus nutrition of corn plants. With the use of such fertilizers (OMF-II), plants formed a more powerful root system with improved morphological indicators and an increased absorption surface. The experimental plant's roots weight exceeded the control samples by 28%. Such changes in the indicators of the root system led to a significant increase in the roots volume and the rhizosphere cell of the soil, where numerous chemical and biological transformations, sorption, desorption, and absorption take place. In addition, this indicates the absence of toxic effects of macro- and microelements, which contain the studied OMF-II. Namely, the imbalance of elements in the nutrition system leads to extremely negative consequences – a decrease in the productivity of crops and a deterioration of quality indicators.

Table 5. Yield and quality of Moskito corn hybrid, 2018

Treatment	Crop yields (t/ha)					Yield increase		Content (%)		
	replication				Average					
	1	2	3	4		t	%	starch	fat	albumen
$N_{165}P_{87}K_{32}$ – background	10.8	10.5	9.9	11.2	10.6	–	–	73.3	3.3	7.0
Background + OMF -II (0.5 t/ha)	12.9	13.5	12.2	13.7	13.0	2.4	22.6	73.2	3.5	7.8
HIP_{05}	0.53	0.64	0.79	0.75	0.77					

The data from determining the grain productivity of one plant were positively correlated with the obtained grain yield on the corresponding experimental plots. The yield increase (2.4 t/ha) compared to the control by 22.6% with the additional application of nutrients to the soil in the form of OMF-II according to the economic background N165P87K32 (table 5). This indicator significantly exceeds the average statistical yield of this crop in Ukraine (6.4-7.0 t/ha) due to the increase in the gross content of the main nutrients and their availability in the soil of the experimental site. It is known that the corns yield is formed due to precipitation, solar radiation and air temperature. Therefore, in our opinion, very favourable climatic conditions in July-August had a significant impact on the increase in yield in the reporting year. During this period, more than 155 mm of precipitation fell compared to the same months in 2017, which contributed to the optimization of mineral nutrition, growth and development of corn plants in a critical period regarding moisture. The high yield of the Moskito hybrid with the application of our OMF is probably due to the intensive supply of photoassimilants to the grains. The conducted analysis of the grain of the corn of Moskito confirms that it was suitable for food, fodder, technical needs and export. The increase in productivity with the OMF use strengthens the "effect of growth dilution". The 1000 grains mass, and therefore the grains size, increased significantly, while the rate of accumulation of proteins and fats did not change significantly. The introduction of OMF 0.5 t/ha into the corn fertilization system contributed to the formation of grain with better protein content – 7.8% compared to the control – 7.0%, where only mineral fertilizers were applied. The fertilization system did not affect the starch content in the grain (table 5). This indicator remained at the level of 73%.

Among grain crops, corn has the highest uptake and assimilation coefficient of macro- and microelements from the soil. For the formation of one grain ton and the corresponding number of vegetative organs, it takes from the 1 ha soil, kg/ha: N – 20-30, P_2O_5 – 8-10, K_2O – 15-17, as well as a lot of calcium, magnesium (Mg) – 6-10, sulfur (S) – 4-5, manganese (Mn) – 0.15, zinc (Zn) – 0.05-0.1, boron (B) – 0.01-0.02, molybdenum (Mo) – 0.01, iron (Fe) – 0.2 and other trace elements. Traditionally, this culture is considered an "indicator" of the content of trace elements in the soil. Corn is sensitive to their use, especially zinc (Zn), manganese (Mn), copper (Cu) and boron (B), the lack of which slows down plant growth and development and reduces crop productivity [35, 36]. As evidenced by the data of the elemental analysis of the ash of the plant samples of the Moskito hybrid corn (table 6), the grain did not contain such dangerous elements as cadmium, lead, or copper.

Taking into account the importance of wheat as a leading crop in Ukraine's agriculture and negative forecasts regarding global climate changes, the development of environmentally safe and effective prolonged action organo-mineral fertilizer, which would ensure the improvement of mineral nutrition of plants and increase their drought and frost resistance, is important and relevant. The winter wheat yield is directly dependent on the quantitative expression of each structural element. Its value is an integral indicator of productivity by phases of plant growth and development. Our structural analysis shows that all structure elements participate in the crop formation and change depending on the level of phosphorus supply to the plants and weather conditions. The size of the ear and its filling with grain are important elements of the crop structure that directly affect plant productivity. As shown by the data (table 7), with the additional application of nutrients in the form of BG-II fertilizers, there was a significant increase in the indicator – the grains number per ear by 85% in the version where 0.6 t/ha was applied in the background and by 74% – in variant with the application rate of 1.0 t/ha. The results of our research indicate a significant increase (up to 72%) in the Mulan winter wheat plants' productive tilling compared to the control with the application of BG fertilizers at a dose of 1.0 t/ha and by 56% at – 0.6 t/ha. It was characteristic of the Mulan variety that the mass of grains both from the main ear and the side shoots did not depend on the fertilization options. Therefore, the following indicators influenced the overall productivity of plants: synchronous

Table 6. Moskito corn hybrid ash composition (%mass) of using OMF-II in the field experiment, 2018 (XRF).

Treatment		CaO	Fe_2O_3	Cl	K_2O	P_2O_5	MnO	SiO_2	TiO_2	ZnO	SrO
$N_{165}P_{87}K_{32}$ – background	leaf	16.63	0.393	–	19.332	3.924	0.381	43.748	0.090	ppm 93	ppm 139
	stalk	10.93	0.181	–	43.398	5.882	0.170	30.104	–	–	ppm 197
	roots	2.619	3.234	–	18.079	1.727	–	62.427	0.831	ppm 93	–
	grain	–	0.265	–	42.51	44.921	–	1.2	–	0.117	–
Background + OMF -II (0.5 t/ha)	leaf	19.936	0.502	–	26.622	6.310	0.438	47.481	0.117	–	ppm 146
	stalk	10.238	0.687	0.261	43.847	5.971	0.213	36.665	0.156	–	–
	roots	4.70	3.562	0.321	38.871	4.575	0.134	44.618	0.781	ppm 138	–
	grain	–	0.267	–	49.119	45.828	–	–	–	0.100	–

Table 7. The influence of fertilization options on the structural indicators of Mulan winter wheat F2 hybrid (*Triticum aestivum L.*) grain yield, 2019.

Treatment	Number of productive stems (pcs)	Grains number per main ear (pcs)	1000 grains weight (g)	Grain productivity of one plant (g)
Control	2.5±0.1	24.5±1.0	45.3±1.5	2.6±0.15
Background + BG-II (0.6 t/ha)	3.9±0.1	45.4±1.3	45.6±1.3	4.2±0.20
Background + BG-II (1 t/ha)	4.3±0.2	42.7±1.2	44.5±1.4	4.0±0.18

development of the main and side stems, high productive tilling, and ears graininess.

The results of a field experiment with Mulan winter wheat F2 hybrid (*Triticum aestivum L.*) (table 8) show that the harvest yield of the experimental wheat plants depended on the fertilization options, the weather conditions occurred during the phase of the emergence of the plants into the tube, milk ripeness and as well as on the grain size of the ear, the number of productive stems on the plant. Our BG-II introduction into the fertilization system and favourable weather conditions ensured the improvement of experimental plants' nitrogen-phosphorus nutrition. It allowed obtaining an additional harvest of winter wheat grain of 2.5 t/ha using BG-II fertilizer at a dose of 0.6 t/ha and – 1.5 t/ha for the use of 1 t/ha BG-II (table 8).

The main task of rational fertilization system is to achieve a positive balance of nutrients. Recently, in connection with the decrease in the use of organic and mineral fertilizers in many farms of Ukraine, the balance of the main nutrients has become negative, which caused a decrease in soil fertility. Therefore, knowledge of the ways of nutrients loss and their supply is very important for the optimal fertilizer application systems development. Obtaining an increase in

Table 8. Yield and quality of Mulan winter wheat F2 hybrid (*Triticum aestivum L.*), 2019.

Treatment	Crop yields (t/ha) replication					Yield increase		Content (%)
	1	2	3	4	Average	t	%	albumen
Control	5.3	5.6	5.4	5.3	5.4	–	–	12.2
Background + BG-II (0.6 t/ha)	7.4	7.9	7.6	7.9	7.9	2.5	46	12.8
Background + BG-II (1 t/ha)	7.0	7.3	6.6	6.7	6.9	1.5	28	13.0
HIP_{05}	0.26	0.32	0.30	0.31	0.30			

yield is associated with additional nitrogen and phosphorus absorption by experimental plants of Mulan winter wheat F2 hybrid (*Triticum aestivum L.*) with the application of BG-II fertilizers. As a result of the conducted research, a high positive correlation (r=0.9) was established between the grain productivity of one plant, grain size of the ear, productive tilling and grain yield. The quality of winter wheat grain largely depends on varietal and genetic characteristics, soil and climatic conditions, as well as on the basic nutrients supply. However, the fertilizers application is one of the most effective means that causes changes in the chemical composition of plants and increases the grain quality. There are conflicting data on the effect of an increased phosphorus nutrition's level on protein content and grain technological quality. Some authors point to the positive effect of phosphorus nutrition on grain quality, which is that excess nitrogen delays protein synthesis and encourages the accumulation of ammonia and nitrate nitrogen, which is harmful to plants, and phosphorus prevents this unwanted process. As shown in table 8, under favorable weather conditions, balanced nutrition with the introduction of our fertilizers (BG-II), the protein content increased by 6.6%. In the control, the experimental grain contained 12.2% protein (3rd grade, filler), then with the introduction of BG-II at a dose of 1t/ha, this indicator improved to 13.0% (2nd grade).

The elemental analysis (table 9) of the Mulan winter wheat F2 hybrid (*Triticum aestivum L.*) plant samples ash allows us to state that when BG-II was added to its fertilization system, the grain did not contain such dangerous elements as cadmium, lead, copper, and others.

The presence of calcium in the composition of our organo-mineral fertilizers is a source of replenishment of the soil, affects the fixation of organic substances in it, which provides favorable conditions for the formation of soil optimal physical properties. The organic carbon contained in such fertilizers ensures a positive balance of humus in the soil. Such fertilizers can

Table 9. Mulan winter wheat F2 hybrid (*Triticum aestivum L.*) ash composition (%mass) of using BG-II in the field experiment, 2019 (XRF).

Treatment		CaO	Fe_2O_3	Cl	K_2O	P_2O_5	MnO	SiO_2	SO_2	ZnO
Control	stalk	4.774	0.123	0.930	35.463	7.535	–	47.595	2.278	ppm 173
	grain	3.713	0.615	–	41.263	46.235	0.608	–	0.225	0.248
Background + BG-II (0.6 t/ha)	stalk	3.539	0.105	1.923	46.126	2.731	–	33.776	1.209	ppm 179
	grain	5.383	0.569	-	47.6	44.929	0.946	–	0.284	0.289
Background + BG-II (1.0 t/ha)	stalk	3.934	0.132	1.821	46.031	2.931	–	35.427	1.394	ppm 158
	grain	4.463	0.379	–	44.179	43.086	0.569	–	0.340	0.215

be used as an effective ameliorant, especially for acidic (podzolic) soils because they have a slightly alkaline reaction. In addition, it should be added that the introduction of such organo-mineral fertilizers in increased doses can significantly change the nitrogen balance in the soil from non-hydrolyzed forms to mineral and easily accessible to plants, improve phosphorus-potassium nutrition (increase the content of mobile compounds of phosphorus and potassium in the soil), increase the content of clay-mineral particles in the upper genetic layer, which will probably lead to soil cultivation due to the high content of sulfates and calcium carbonates in the composition of organo-mineral fertilizers.

4. Conclusion

High-temperature thermolysis of lignocellulosic waste was carried out with the production of combustible gases at a laboratory facility. It was established that under the conditions of thermolysis, a gas with a calorific value of 5400-6500 J/m^3 is formed in the air, and under inert conditions – 10,000-12,000 J/m^3, and a carbon residue with a calorific value of 18,000-20,000 J/m^3. It's shown that high-ash carbon after the process can be a precursor in the production of silicon oxides and carbides, as well as be one of the important components of organo-mineral fertilizers. With the help of the proposed disposal of wastewater treatment plant sludge ash and plant waste into agrochemically effective fertilizer, we can solve such problems as reducing the volume of accumulated sediment at aeration stations, while involving a valuable source of calcium, phosphorus and some biogenic trace elements in the composition of such necessary products for modern agricultural production. The growing shortage of food, which is associated with the increase in the population and the depletion of agricultural land, the predicted ecological crisis, the expected global warming, as well as the high requirements (standards) that are currently being set for agricultural products, make it urgent to solve the issue of introducing new, environmentally safe, natural organo-mineral fertilizers.

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References

[1] Owusu P A and Asumadu-Sarkodie S 2016 *Cogent Engineering* **3**(1) 1167990 URL https://doi.org/10.1080/23311916.2016.1167990
[2] Rahman S 2007 *IEEE Power and Energy Magazine* **5** 82–83 URL https://doi.org/10.1109/MPAE.2007.329198
[3] Wasiak A L (ed) 2021 *Alternative Energy Sources* (Basel, Switzerland: MDPI) URL https://doi.org/10.3390/books978-3-0365-0375-2
[4] Sutton D, Kelleher B and Ross J R 2001 *Fuel Processing Technology* **73**(3) 155–173 URL https://doi.org/10.1016/S0378-3820(01)00208-9
[5] Albertazzi S, Basile F, Brandin J, Einvall J, Hulteberg C, Fornasari G, Rosetti V, Sanati M, Trifirò F and Vaccari A 2005 *Catalysis Today* **106**(1) 297–300 International Conference on Gas-Fuel 05 URL https://doi.org/10.1016/j.cattod.2005.07.160
[6] Khan S, Paliwal V, Pandey V V and Kumar V 2015 *International Advanced Research Journal in Science, Engineering and Technology (IARJSET)* **2**(Sp1) 301–304 URL https://www.researchgate.net/publication/319456142
[7] You Z, You S and Ma X 2018 *IOP Conference Series: Earth and Environmental Science* **108**(5) 052032 URL https://doi.org/10.1088/1755-1315/108/5/052032
[8] Janiszewska D and Ossowska L 2022 *Energies* **15**(18) 6756 URL https://doi.org/10.3390/en15186756
[9] Selvarajoo A 2020 *IOP Conference Series: Earth and Environmental Science* **489**(1) 012033 URL https://doi.org/10.1088/1755-1315/489/1/012033

[10] Zeller-Powell C E 2011 *Defining Biomass as a Source of Renewable Energy: The Life-Cycle Carbon Emissions of Biomass Energy and a Survey and Analysis of Biomass Definitions in States' Renewable Portfolio Standards, Federal Law, and Proposed Legislation* A thesis presented to the Environmental Studies Program and the Graduate School of the University of Oregon in partial fulfillment of the requirements for the degree of Master of Science University of Oregon URL https://scholarsbank.uoregon.edu/xmlui/handle/1794/11483

[11] Maisyarah L and Siregar Y 2021 *IOP Conference Series: Materials Science and Engineering* **1122**(1) 012080 URL https://doi.org/10.1088/1757-899X/1122/1/012080

[12] He P, Zhang Q, Zhang B, Liu J, Gong G and Li D 2020 *IOP Conference Series: Materials Science and Engineering* **721**(1) 012002 URL https://doi.org/10.1088/1757-899X/721/1/012002

[13] Wang G, Dai Y, Yang H, Xiong Q, Wang K, Zhou J, Li Y and Wang S 2020 *Energy & Fuels* **34**(12) 15557–15578 URL https://doi.org/10.1021/acs.energyfuels.0c03107

[14] Hu X and Gholizadeh M 2019 *Journal of Energy Chemistry* **39** 109–143 URL https://doi.org/10.1016/j.jechem.2019.01.024

[15] Fahmy T Y A, Fahmy Y, Mobarak F, El-Sakhawy M and Abou-Zeid R E 2020 *Environment, Development and Sustainability* **22** 17–32 URL https://doi.org/10.1007/s10668-018-0200-5

[16] Bridgwater A V and Peacocke G V C 2000 *Renewable and Sustainable Energy Reviews* **4**(1) 1–73 URL https://doi.org/10.1016/S1364-0321(99)00007-6

[17] Venderbosch R H and Prins W 2010 *Biofuels, Bioproducts and Biorefining* **4**(2) 178–208 URL https://doi.org/10.1002/bbb.205

[18] Nair R R, Mondal M M, Srinivasan S V and Weichgrebe D 2022 *Materials* **15**(12) 4130 URL https://doi.org/10.3390/ma15124130

[19] Liu L, Liu Y, Wang W, Wang Y, Li G and Hu C 2021 *Toxins* **13**(8) 542 URL https://doi.org/10.3390/toxins13080542

[20] Lamers F, Cremers M, Matschegg D, Schmidl C, Hannam K, Hazlett P, Madrali S, Dam B P, Roberto R, Mager R, Davidsson K, Bech N, Feuerborn H J and Saraber A 2018 Options for increased use of ash from biomass combustion and co-firing Tech. Rep. Task 32: Biomass Combustion and Cofiring IEA Bioenergy URL https://www.ieabioenergy.com/wp-content/uploads/2019/02/IEA-Bioenergy-Ash-management-report-revision-5-november.pdf

[21] Sindhu R, Gnansounou E, Rebello S, Binod P, Varjani S, Thakur I S, Nair R B and Pandey A 2019 *Journal of environmental management* **241** 619—630 URL https://doi.org/10.1016/j.jenvman.2019.02.053

[22] Sharholy M, Ahmad K, Mahmood G and Trivedi R C 2008 *Waste Management* **28**(2) 459–467 URL https://doi.org/10.1016/j.wasman.2007.02.008

[23] Bouhia Y, Hafidi M, Ouhdouch Y, Boukhari M E M E, Mphatso C, Zeroual Y and Lyamlouli K 2022 *Reviews in Environmental Science and Bio/Technology* **21** 425–446 URL https://doi.org/10.1007/s11157-022-09619-y

[24] Petrychenko V, Korniychuk O and Zadorozhna I 2018 *Bulletin of Agricultural Science* (11) 54–62 URL https://doi.org/10.31073/agrovisnyk201811-08

[25] Wang S, Liu C, Han L, Li T, Yang G and Chen T 2022 *Agriculture* **12**(7) 976 URL https://doi.org/10.3390/agriculture12070976

[26] Cadot S, Bélanger G, Ziadi N, Morel C and Sinaj S 2018 *Nutrient Cycling in Agroecosystems* **112** 417–433 URL https://doi.org/10.1007/s11157-022-09619-y

[27] Pettigrew W T 2008 *Nutrient Cycling in Agroecosystems* **133**(4) 670–681 URL https://doi.org/10.1111/j.1399-3054.2008.01073.x

[28] Kashkovsky V I, Aksylenko M D, Kamenskyh D S and Yevdokymenko V O 2018 *Agroecological journal* (1) 57–65 URL https://doi.org/10.33730/2077-4893.1.2018.160536

[29] Kashkovsky V I, Yevdokymenko V O, Kamenskyh D S, Tkachenko T V and Vakhrin V V 2017 *Science and Innovation* **13** 51–61 URL https://doi.org/10.15407/scine13.03.051

[30] Dospekhov B A 1985 *Field Experience Method* (Moscow: Agropromizdat)

[31] Hrytsaienko Z M, Hrytsaienko A O and Karpenko V P 2003 *Methods of biological and agrochemical studies of plants and soils* (Kyiv: ZAT Nichlava)

[32] Mlonka-Mędrala A, Evangelopoulos P, Sieradzka M, Zajemska M and Magdziarz A 2021 *Fuel* **296** 120611 URL https://doi.org/10.1016/j.fuel.2021.120611

[33] Tkachenko T, Yevdokymenko V, Kamenskyh D, Povazhny V, Filonenko M, Kremenetskii V, Vakhrin V and Kashkovsky V 2020 *Nanosystems, Nanomaterials, Nanotechnologies* **10** 669–679 URL https://doi.org/10.15407/nnn.18.03.669

[34] Tkachenko T, Yevdokymenko V, Kamenskyh D, Povazhny V, Sheludko Y, Vakhrin V and Kashkovsky V 2020 *Applied Nanoscience* **10** 4617–4623 URL https://doi.org/10.1007/s13204-020-01383-1

[35] Guryev B P, Luk'yanenko L M, Kozubenko L V, Meyerzon Y Y and Virmenko L I 1992 *Plant Breeding and*

Seed Production 14–18 URL https://doi.org/10.1007/s13204-020-01383-1
[36] Kalashnikov N P, Tikhonchuk P V and Fokin S A 2020 *IOP Conference Series: Earth and Environmental Science* **547**(1) 012043 URL https://doi.org/10.1088/1755-1315/547/1/012043

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Extraction of sulfur (IV) oxide, nitrogen oxides and carbon oxide from flue gases using a sorbent under conditions of its mechanical activation

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Extraction of sulfur (IV) oxide, nitrogen oxides and carbon oxide from flue gases using a sorbent under conditions of its mechanical activation

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Abstract. TThe paper substantiates the feasibility of creating an adsorption technology with controlled activation of the adsorbent for the removal of sulfur dioxide, nitrogen oxides, and carbon from the flue gases of coal-fired power plants. In laboratory conditions, the effect of mechanical activation on the adsorption capacity of ash was studied. It is shown that the controlled mechanical activation is able to increase the adsorption capacity of ash relative to sulfur dioxide by 2.7 times, to nitrogen oxides by 2.1 times, to carbon monoxide by 5 times or more.

1. Introduction

The National Report on the State of the Environment in Ukraine in 2020 [1], shows that 3.8 tons of pollutants were present per square kilometer of the country's territory. The main chemical components entering the atmospheric air from stationary sources are substances in the form of suspended solid particles – 248.9 thousand tons (11.1% of the total volume of pollutants), dioxide and other sulfur compounds – 782.1 thousand tons (34.9%), methane – 429.1 thousand tons (19.1%), nitrogen oxide – 3.4 thousand tons (0.15%), carbon monoxide – 707.3 thousand tons (31.5%). Almost 37.9 % of pollution from stationary sources comes from the energy sector, mainly thermal power plants. In Ukraine, flue gases from coal-fired power plants, boilers, and heaters are released into the environment without treatment. The problem of atmospheric air pollution in Ukraine with toxicants remains relevant.

Independent researchers [2] also confirm the significant damage that flue gases from coal-fired power plants cause to the environment. According to this report, Ukraine is one of the leaders in Europe in terms of atmospheric air pollution with sulfur and nitrogen emissions emitted together with the flue gases of coal-fired power plants. Among the thirty coal-fired power plants in Europe that pollute SO_2 the most, 12 belong to Ukraine. Ukraine ranks second in Europe in air pollution with nitrogen oxides. Ukraine produces 34% of its electricity consumption from 20 coal-fired power plants built before 1976, none of which have desulfurization equipment. Therefore, the task of cleaning flue gases of coal-fired power plants from sulfur, nitrogen and carbon oxides is extremely relevant in the European context.

There are a lot of various studies aimed at improving coal combustion processes and implementing technological processes that reduce emissions of sulfur oxides, nitrogen, and carbon. Zaporozhets et al [3] provides statistical studies of emissions into the atmosphere by stationary and mobile sources of pollution in Ukraine for 1990–2018. It also indicates the need to reduce emissions of toxicants into the atmosphere. This can be achieved through the introduction of new technological processes at coal-fired power plants.

Chernyavsky et al [4] summarizes the experience of burning coal mixtures at three power plants of Ukraine. The issues of production, grinding, burning of mixtures and ecological aspects of their use are considered. Popov et al [5] shows that burning coal leads to the accumulation of ash and slag waste. Although they are environmental pollutants, under the right conditions these wastes can become a sorbent and be used in technologies for the adsorption of sulfur oxides, nitrogen and carbon from flue gases. Moreover, flue gases are formed in the same combustion processes where these solid ash and slag wastes are formed.

Volchyn et al [6] established an analytical relationship between SO_2 emissions in flue gas at coal-fired thermal power plants and the ash content of Ukrainian thermal coal. Thus, the research data indirectly indicate the possibility of controlling the sulfur oxide content due to technological processes aimed at ash activation. Schmauss and Keppler [7] show that sulfur dioxide is actively adsorbed by volcanic ash, so it can be concluded that ash from burning coal will similarly adsorb SO_2. Walawska et al [8] proves that the mechanical activation of solid particles significantly improves their characteristics as adsorbents for SO_2. Wu et al [9] proves that different modes of mechanical activation of coal slag significantly change its physicochemical characteristics and adsorption capacity. That is, mechanical activation of coal ash is potentially able to improve the adsorption of sulfur dioxide and other toxicants from flue gases. Shukor et al [10] studied the adsorption of sulfur dioxide by carbon. Carbon is also contained in ash as a product of incomplete combustion of coal, so the adsorption characteristics of coal ash may partially depend on its carbon content. Articles [11, 12] show that carbon can also actively adsorb nitrogen oxides.

The analysis of the literature showed that when burning coal at TPPs, solid wastes are formed – ash and slag, and gaseous wastes – oxides of sulfur, nitrogen, and carbon. At the same time, it is possible to create such a technological process, when the solid emission – ash, will be mechanically activated and will adsorb oxides of sulfur, nitrogen, and carbon. Such a technology, provided it is created, has a real perspective for implementation at coal-fired thermal power plants of Ukraine and Europe. The idea of creating such a technology emerged as a result of own research [13] of various chemical processes, when mechanical and chemical activation of the catalyst significantly accelerated chemical transformations. Adsorption is one of the stages of catalysis, so mechanical activation of MA can affect adsorption as a separate process. Studies of processes using coal as a raw material [14, 15] have shown that coal can be mechanically activated. This formed the basis of this work, where ash from coal combustion was activated under controlled conditions. This increased its sorption capacity relative to sulfur dioxide, nitrogen oxides, and carbon monoxide. Research results can become the basis of technology for removing toxicants from flue gases of coal-fired power plants.

2. Laboratory equipment and methodology of the experiment

The laboratory unit for researching the process of adsorption from flue gases under the conditions of mechanical activation is presented in figure 1.

Adsorption of nitrogen oxides, sulfur oxide (IV), and carbon monoxide was studied. Ash from burning coal and zeolites of various types were used as a sorbents. Before the start of the experiment, the V-1 tank is filled with a mixture of air, sulfur oxide (IV), nitrogen, and carbon, which is an analogue of flue gases produced during the burning of coal at power plants in different modes. The obtained gas mixture enters Ads adsorber from above. The adsorber is filled with sorbent and dispersing material.

The temperature in the adsorber is maintained by an electric heater H, measured by a

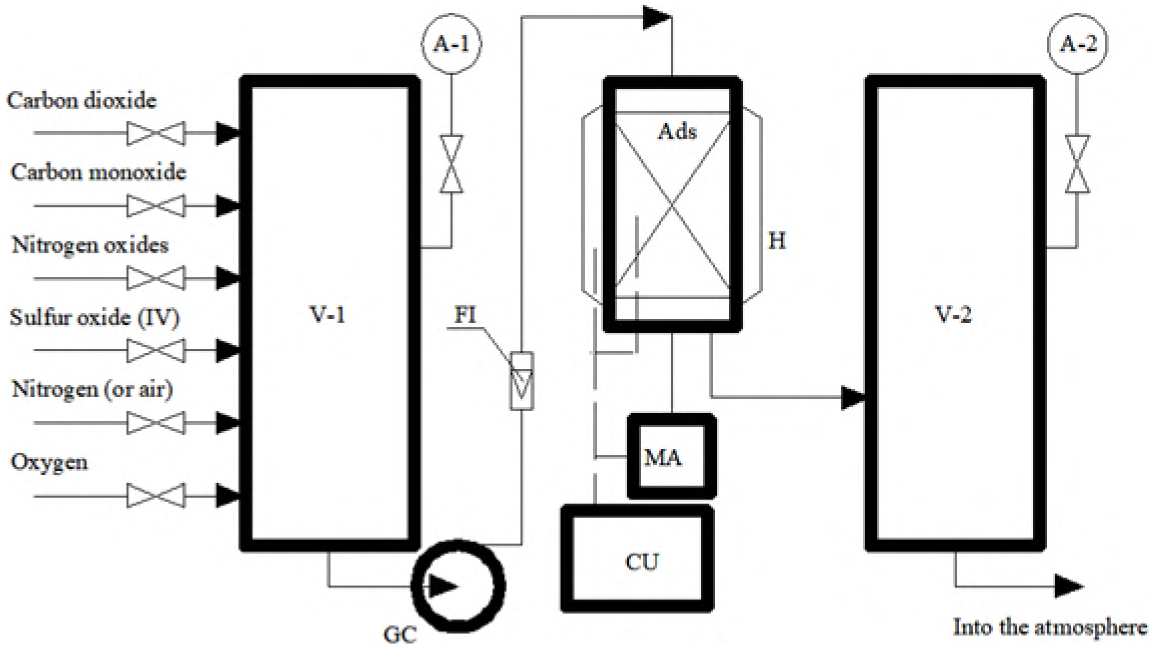

Figure 1. Laboratory unit for studying the process of adsorption of substances from flue gases using mechanical activation. CU – control unit; V-1 – container with a gas mixture; A-1-2 – gas mixture analysis points; H – electric heater; Ads – reactor-adsorber; MA – vibrating device; GC – compressor; V-2 – receiver of adsorbed gases; FI – rotameter.

thermocouple. The activation of raw materials in the adsorber is carried out by forced mechanical oscillations with the help of an vibrating device MA. The temperature in the reaction zone and the intensity of activation are set and maintained by the control unit CU. When the adsorber moves with a certain frequency and amplitude, a vibro-thinned layer of dispersing particles is created and mechanochemical activation of the sorbent surface by them. A metal felt filter is located at the outlet of the adsorber, which prevents the removal of sorbent particles from the adsorption volume. Gases from the adsorber enter the V-2 receiver. Pumping of the gas mixture from V-1 to V-2 is carried out by the compressor GC. The unit has two sampling points of the gas mixture for analysis: the initial mixture and the final products. The content of oxides of nitrogen, sulfur and carbon is determined by a portable gas analyser OKSY-5M-5H with an error of ±5 ppm.

The volume of the laboratory adsorber is 8 cm^3, the capacity for gases is 50 liters. At a gas supply rate of 5-25 l/h, the duration of the experiment is 2-8 hours. Variable parameters during the experimental work were: temperature, flow rate of the gas mixture, concentration of gases in the mixture, vibration frequency of the vibrating device.

3. Research procedure

The AnC theory allows predicting intensification by mechanical activation of not only chemical transformations, but also other stages of the catalytic process, for example, the adsorption stage. Thus, it is possible to distinguish a separate direction of research – mass exchange processes. The degree of sorption and sorption capacity are highly dependent on temperature, intensity of activation, type of sorbent. The dependence of sorption efficiency and sorption capacity passes through maxima and is very similar to the dependence of the degree of transformation and the speed of chemical reactions on the frequency of mechanochemical activation in processes that take place using aerosol nanocatalysis technology. This indicates that sorbent activation is very similar in nature to catalyst activation. figure 2 shows the effect of mechanical on the sorption capacity of the sorbent – coal ash – relative to sulfur oxide (IV).

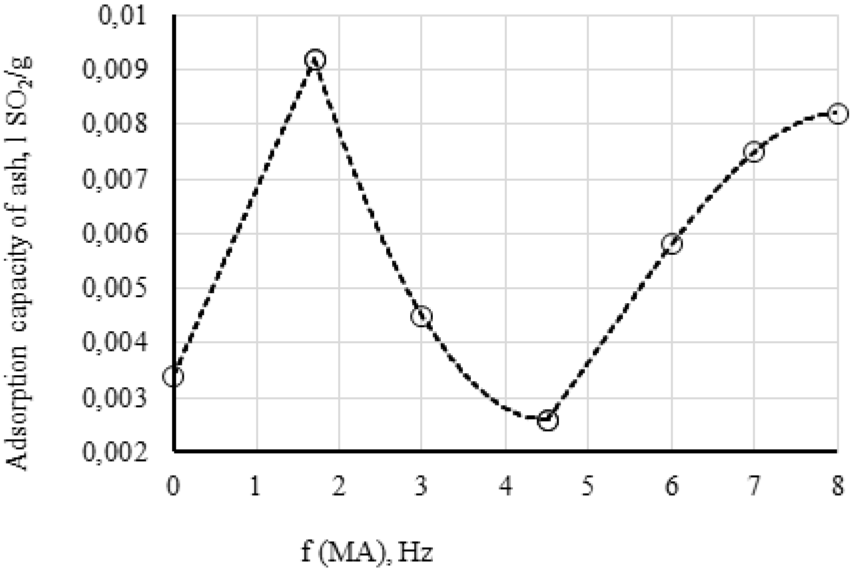

Figure 2. The effect of MXA on the adsorption capacity of ash in relation to SO_2 at 473K.

The presence of a maximum of the adsorption capacity at an MA intensity of 1.7 Hz and a tendency to a second maximum at an MA slightly higher than 8.0 Hz is observed. The dependence is described by equations (1).

The capacity achieved with the help of MA adsorption is such that it provides effective purification from sulfur oxides of flue gases from the burning of energy grades of coal with an ash content of 30%.

$$\begin{gathered}\theta = 0.0034f + 0.0034,\ \text{(0-1.7 Hz)};\\ \theta = 0.0008f^2 - 0.0076f + 0.0196,\ \text{(1.7-4.5 Hz)};\\ \theta = -10^{-5}f^3 + 0.0015f^2 - 0.0054f + 0.006,\ \text{(4.5-8.0 Hz)};\end{gathered} \tag{1}$$

The use of MA is able to increase the adsorption capacity of ash by 2.7 times at a temperature of 423K, i.e. it allows to organize an industrial technology for removing sulfur oxides without cooling flue gases, which will significantly reduce energy costs on the scale of an industrial process. The use of ash from the burning of the same coal as a sorbent will allow reducing material costs on the scale of the industrial process. The process is able to provide 100% removal of SO_2 when its content in flue gases is up to 650 ppm (a typical amount for flue gases from burning low-quality thermal coal with an excess of 1.25 air) at an adsorbent concentration of 60 g/m^3 of flue gases.

In figure 3 shows the effect of MA on the adsorption capacity of the same ash in relation to nitrogen oxides. The values are in the same range as for SO_2.

The use of MA is able to increase the sorption capacity of ash in relation to nitrogen oxides by 2.1 times at a temperature of 423K and ensure 100% removal of NO_x from flue gases from the burning of thermal coal at a concentration of sorbent (ash) at the level of 20 g/m^3 of flue gases, which corresponds to the technological mode of combustion at industrial plants. This cleaning technology does not even require an additional amount of adsorbent.

The presence of a maximum of the adsorption capacity at an intensity of MA near 3.0 Hz and a tendency to a second maximum at an MA above 8.0 Hz is observed. The dependence is

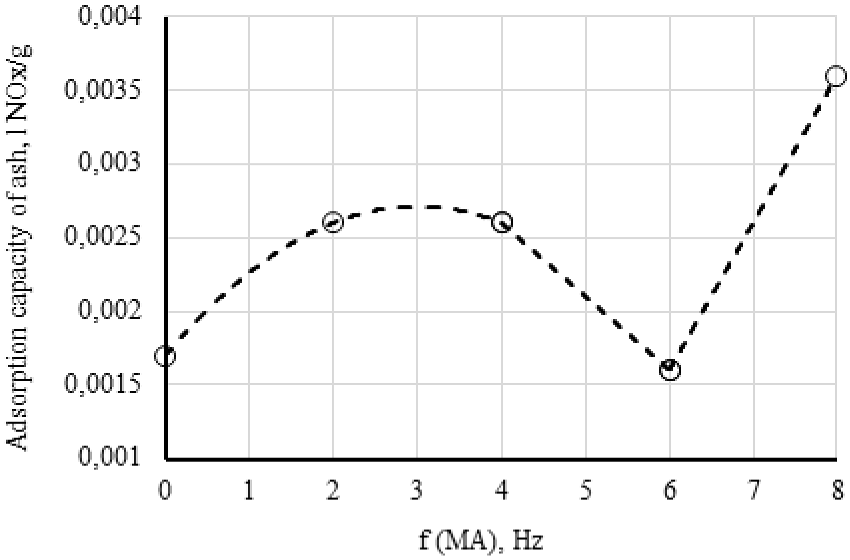

Figure 3. The influence of MA on the adsorption capacity of ash in relation to NO_x at 473 K.

described by equations (3). The capacity achieved with the help of MA adsorption is such that it provides effective cleaning of flue gases from the combustion of energy grades of coal with an ash content of 30% and a NO_x content of up to 250 ppm from nitrogen oxides.

$$\begin{gathered} \theta = -0.0001x^2 + 0.0007x + 0.0017, \text{ (0-4.0 Hz)}; \\ \theta = -0.0005x + 0.0046, \text{ (4.0-6.0 Hz)}; \\ \theta = 0.001x - 0.0044, \text{ (6.0-8.0 Hz)}; \end{gathered} \tag{2}$$

In some modes of coal burning at thermal power plants, carbon monoxide formation is possible, so it is advisable to study the ability of ash to adsorb it as well. In figure 4 shows the influence of MA on the adsorption capacity of ash in relation to CO, and the change in adsorption capacity from MA is described by equations (3), (4).

$$\theta = 0.0019f, \text{ (0-1.2 Hz)}; \tag{3}$$

$$\theta = -0.0004f^3 + 0.0038f^2 - 0.0112f + 0.011, \text{ (1.2-4.0 Hz)}; \tag{4}$$

For carbon monoxide, the influence of MA is particularly noticeable. In the absence of MA, it was not adsorbed at all under the experimental conditions. The use of MA at the level of 1.2 Hz made it possible to increase the adsorption capacity of carbon monoxide by more than 5 times in comparison with other modes of MA.

4. Conclusions

The development of technological processes capable of removing oxides of sulfur, nitrogen, and carbon from flue gases of coal-fired power plants is an urgent scientific and practical task. Adsorption processes using ash from the burning of the same coal as an adsorbent are promising.

The use of controlled mechanical activation can significantly affect the adsorption capacity of ash relative to oxides of sulfur, nitrogen, and carbon.

It is shown that the controlled mechanical activation is able to increase the adsorption capacity of ash relative to sulfur dioxide by 2.7 times, to nitrogen oxides by 2.1 times, to carbon monoxide by 5 times or more.

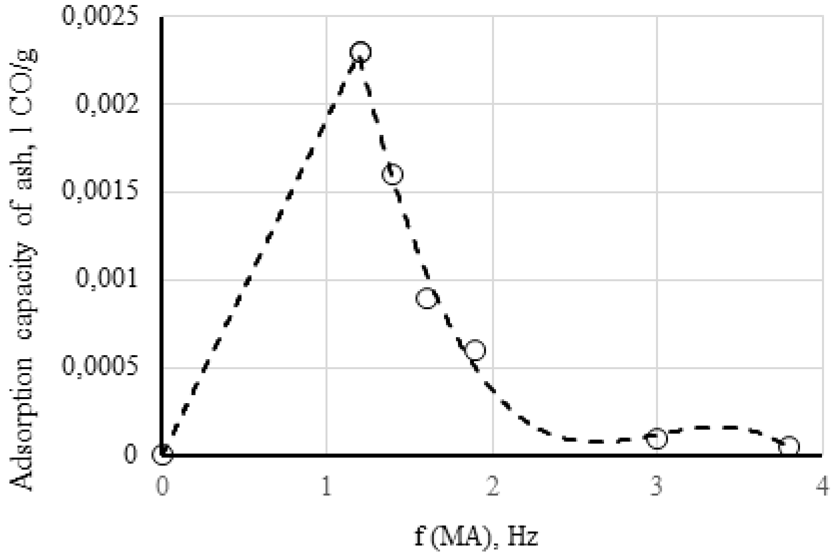

Figure 4. The influence of MA on the adsorption capacity of ash in relation to CO at 473 K.

A mathematical description of the influence of MA intensity on the adsorption capacity of ash relative to oxides of sulfur, nitrogen, and carbon is provided. This makes it possible to optimize the MA regime to achieve the most effective adsorption capacity of ash.

The research results can form the basis for the creation of industrial technology designed for the purification of flue gases of coal-fired power plants from sulfur dioxide, nitrogen oxides and carbon monoxide. But for this, it is still necessary to study the desorption stage and to propose ways of chemical binding of concentrated oxides of sulfur, nitrogen, and carbon into non-toxic products.

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References

[1] 2022 Natsionalna dopovid pro stan navkolyshnoho pryrodnoho seredovyshcha v Ukraini u 2020 rotsi URL https://mepr.gov.ua/wp-content/uploads/2022/10/Natsionalna-Dopovid-2020-2.pdf

[2] Ufuk A 2021 Coal power air pollution in Europe URL https://ember-climate.org/insights/research/coal-power-air-pollution/

[3] Zaporozhets A, Babak V, Isaienko V and Babikova K 2020 Analysis of the Air Pollution Monitoring System in Ukraine *Systems, Decision and Control in Energy I* ed Babak V, Isaienko V and Zaporozhets A (Cham: Springer International Publishing) pp 85–110 ISBN 978-3-030-48583-2 URL https://doi.org/10.1007/978-3-030-48583-2_6

[4] Chernyavsky M, Provalov O, Kosyachkov O and Bestsennyy I 2021 *Procedia Environmental Science, Engineering and Management* **8**(1) 23–31 URL http://procedia-esem.eu/pdf/issues/2021/no1/4_01.04_Chernyavskiy_21.pdf

[5] Popov O, Iatsyshyn A, Kovach V, Artemchuk V, Kameneva I, Radchenko O, Nikolaiev K, Stanytsina V, Iatsyshyn A and Romanenko Y 2021 *Journal of Health and Pollution* **11**(31) 210910 URL https://doi.org/10.5696/2156-9614-11.31.210910

[6] Volchyn I A, Haponych L S and Przybylski W J 2020 *Naukovyi visnyk natsionalnoho hirnychoho universytetu* 87–93 URL https://doi.org/10.33271/nvngu/2021-5/087

[7] Schmauss D and Keppler H 2014 *American Mineralogist* **99**(5-6) 1085–1094 URL https://doi.org/10.2138/am.2014.4656

[8] Walawska B, Szymanek A, Pajdak A and Nowak M 2014 *Polish Journal of Chemical Technology* **16**(3) 55–62 URL `https://doi.org/10.2478/pjct-2014-0051`
[9] Wu F, Li H and Yang K 2021 *Coatings* **11**(8) 902 URL `https://doi.org/10.3390/coatings11080902`
[10] Shukor N S A, Alias A B, Ishak M A M, Deris R R R, Jawad A H, Radzun K A and Ismail K 2018 *International Journal of Technology* **9**(6) 1121 URL `https://doi.org/10.14716/ijtech.v9i6.2358`
[11] Fang M L, Chang H Y, Chen C H, Lin S L, Hsieh Y K, Chou M S and Chang C Y 2019 *Aerosol and Air Quality Research* **19**(11) 2568–2575 URL `https://doi.org/10.4209%2Faaqr.2019.09.0439`
[12] Anthonysamy S I, Lahijani P, Mohammadi M and Mohamed A R 2020 *Korean Journal of Chemical Engineering* **37**(1) 130–140 URL `https://doi.org/10.4209/aaqr.2019.09.0439`
[13] Glikina I, Glikin M and Kudryavtsev S 2017 *Eastern-European Journal of Enterprise Technologies* **3** 4–8 URL `https://doi.org/10.15587/1729-4061.2017.99022`
[14] Luhovskoi A, Glikina I, Glikin M and Kudryavtsev S 2017 *Eastern-European Journal of Enterprise Technologies* **6** 53–58 URL `https://doi.org/10.15587/1729-4061.2017.118396`
[15] Luhovskoi A, Glikina I, Glikin M and Kudryavtsev S 2018 *Eastern-European Journal of Enterprise Technologies* **4** 56–62 URL `https://doi.org/10.15587/1729-4061.2018.136371`

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Methodology for determining the availability of natural moistening of the territory by hydrometeorological conditions for the needs of land reclamation

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Methodology for determining the availability of natural moistening of the territory by hydrometeorological conditions for the needs of land reclamation

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Abstract. The paper considers one of the important problems of water use – determination of the humidification conditions of the territory for the hydromelioration needs. The methodical approach to determining the probability of exceeding natural moisture by a group of criteria is highlighted. Nowadays there is no single, reliable and simple method for determining this indicator. Assessing climatic conditions, considering their impact on crop productivity, it is necessary to take into account hydrometeorological factors that have a decisive influence on the development of crops and, accordingly, determine their yield. These include, first of all, precipitation, moisture reserves in the soil, evapotranspiration and other complex indicators that allow to take into account the distribution of meteorological factors during the growing season of the crop and their possible negative impact on the development of the plant, because each crop requires a certain optimal regime of soil temperature and moisture at different stages of its development. The article presents the solution of the set tasks on the example of winter wheat crops according to the data of the Dnipro meteorological station (airport).

1. Introduction

The determining factor in the development of agricultural production in the Steppe of Ukraine is natural resources, which are characterized by bioclimatic potential, soil fertility and water regime. According to FAO estimates, Ukraine has the potential for a significant (up to 3 or more times) increase in agricultural production and exports, provided that the available natural resources are used more efficiently. Insufficient level of their use is limited by a number of factors, the main of which is the natural moisture supply deficit on more than 2/3 of the territory of Ukraine.

Thus, significant variability of moisture conditions in Ukraine is the main limiting factor that limits not only the level of crop productivity, but also the use of natural and anthropogenic potential of agriculture.

Many years of agricultural experience and scientific researches show that it is possible to prevent and mitigate the negative effects of climate changing on agricultural production only with the help of irrigated land reclamation [1].

Despite thousands of years of mankind experience in irrigated agriculture, the issue of vegetative irrigation of crops has not been studied enough. The key point here is the methodology for determining the availability of natural moisture in the territory. The correct choice of the year-model in the development of the irrigation regime will prevent serious miscalculations in the design of irrigation systems, waterlogging, flooding and flooding of irrigated lands, which will inevitably lead to secondary salinization and anthropogenic soil pollution and soil degradation in irrigated areas of Ukraine.

The aim is to develop scientific approaches to environmentally safe water use aimed at preventing the growth of anthropogenic impact on the environment, ensuring environmentally safe living conditions for the population and economic activity and protection of water resources from pollution and depletion, rational use of water resources, ensuring sustainable functioning of ecosystems in the river basins of Ukraine, prevention of harmful effects of water and elimination of its consequences.

2. Literature review

The analysis of scientific and normative materials in the field of hydromelioration shows insufficient reliability of existing methods for calculating the availability of natural moisture in the territory, which are used to improve the methods of water use rationing and assessment of the complex impact of hydrometeorological factors and irrigation regimes on crop yields and the ecological condition of reclaimed lands.

It is customary to assess the natural water availability of the territory based on the amount of precipitation during the growing season, climatic indicators, crop water deficit and actual moisture content of the calculated soil layer.

The sum of precipitation is mainly used in agroclimatology to assess the moisture conditions, which is calculated as a cumulative total and graphically represented in the form of integral curves.

Lebedev studied in detail the methods of constructing the curves of availability of various climatic factors and developed a methodology for constructing nomograms of availability of precipitation amounts [2]. Any probabilistic characteristic of climate is given on the basis of analysis of a representative series of observations. The types of curves proposed by Lebedev have great stability in space, which allows them to be used for a large area, including those that do not have a representative series of observations.

Such nomograms are constructed for different territories and they can be used to estimate the availability of natural moisture in the territory. As an example, figure 1 shows such a nomogram for the South of Ukraine [3].

Assessment of the moisture availability in the territory only by the amount of precipitation is insufficient and not always objective, since each year has a specific intra-annual distribution of precipitation uncharacteristic of others. A year with long dry periods and one or two large rains can be equated to a year in which rains fell evenly throughout the growing season, although the humidity of the territory in such conditions will be different. Therefore, to exclude the peculiarities of individual years, it is advisable to consider the frequency of precipitation or take not one, but several years that are closest to the calculated availability and average their meteorological data.

The disadvantage of this method is that not only precipitation affects the humidity of the territory, but also other agrometeorological factors that are not taken into account here.

Therefore, for a more correct and objective determination of the availability of the territory's humidity, various climatic indicators are used, taking into account not only the income (precipitation) component of the water balance of the territory, but also the costs, that is, the so-called meteorological complexes. An example of the application of such systems is the methodology for selecting a year of a given availability by a complex climatic indicator (CCI),

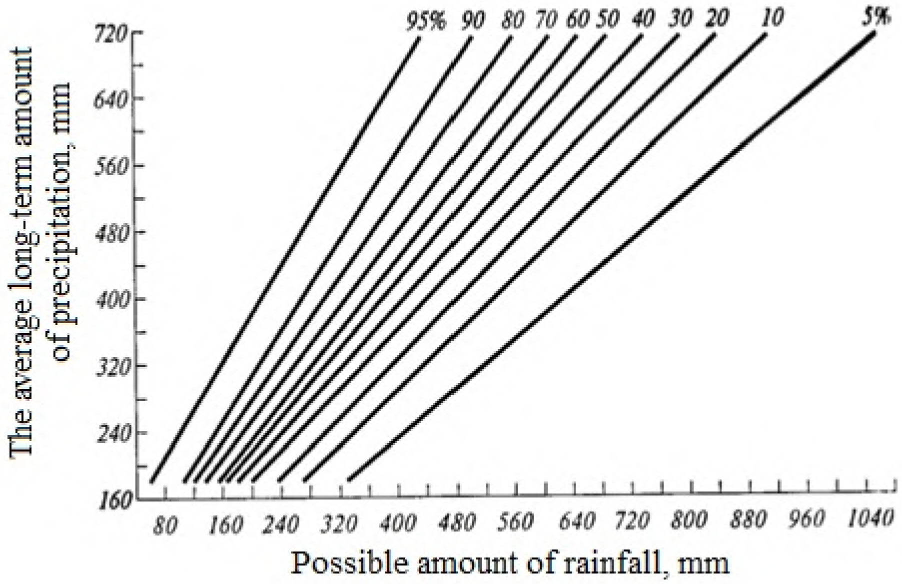

Figure 1. Graph for calculating the amount of precipitation of different availability per year (according to A. M. Lebedev) [3].

which was developed for zones of sufficient and unstable moisture in Ukraine. It is based on the availability integral indicator of CIP_j vegetation values of meteorological factors and meteorological complexes built on their basis [4–6].

The latter is determined by the formula

$$CIP_j = 1 - \frac{\sum\limits_{i=1}^{l} m_{ij}}{l \cdot n_j}, \tag{1}$$

where $\sum\limits_{i=1}^{l} m_{ij}$ – is the sum of places occupied by meteorological factors and complexes of the set $\{i\}$, $i = \overline{1, l}$ is the sum of places occupied by meteorological factors and complexes of the set, in the statistical sequences of their vegetation values for the years of observations reduced to a comparative form $\{j\}$, $j = \overline{1, n_j}$.

The value of the indicator CIP_j defined by (1), vary within $\{0;\ 1\}$ almost never reaching the limit values, which confirms the really complex and ambiguous nature of climate-forming components [6].

The choice of the year of a given availability by crop water consumption deficits by the real year method is carried out by a retrospective series of years, taking into account the composition of crops. According to this series of observations, crop water deficits are determined and their availability is calculated by the statistical method [7].

Water consumption deficits are calculated using total evaporation, which is determined by meteorological factors and biological characteristics of crops. The most widespread in Ukraine are the bioclimatic method [8, 9]; improved bioclimatic method [10]; biophysical method [11].

For a long time, the Penman [12] and Blaney-Criddle [13] methods were widespread in the world. Taking into account some inaccuracy of these methods in 1990, the FAO Council of Experts recommended to approve the combined Penman-Monteith method as a standard for calculating the reference evapotranspiration (ET_0). The method provides for the determination of ET_0 of a hypothetical crop with a height of 0.12 m, a surface resistance of $70\,\text{cm}^{-1}$ and an albedo of 0.23, similar to lawn grass of the same height in the phase of active vegetation and sufficiently moistened. The Penman-Monteith equation is derived from the soil surface energy balance equation, and the dependence of ET_C on ET_0 reflects the crop coefficient K_C, which characterizes the differences between a typical agricultural crop and a reference lawn grass [14–18]. Numerous researchers have analyzed different calculation methods in different regions. As a result, the Penman-Monteith method was adopted worldwide as a standard method for determining evapotranspiration (ET_0). ET from the plant surface under non-standard conditions is given by the stress coefficient (K_S) or modification of the culture coefficient.

Probably the most objective criterion for determining the availability of natural moisture in the territory is the actual moisture reserves in the calculated soil layer. In the presence of a representative series of data on moisture reserves, their availability is also determined by generally accepted statistical methods.

Nowadays, more than 20 methods of soil moisture measurement have been developed. But all of them have certain disadvantages that limit their use – significant time discreteness and uncertain representativeness when transferring their values to other fields or arrays; some of them have low efficiency.

These shortcomings are absent in the calculation methods for determining the content of moisture reserves in the soil. They usually involve the calculation of indirect indicators of moisture content based on previous weather conditions. In some methods, a simplified water balance equation is used, considering the initial soil moisture reserves measured by instrumental methods. It should be noted that errors of instrumental measurements and calculation errors of water balance components significantly reduce the accuracy of these methods. The method of determining daily soil moisture reserves developed at the Dnipro State Agrarian and Economic University is devoid of these shortcomings [19]. Therefore, in our research, we will use this method in assessing the natural availability of the territory by soil moisture reserves.

3. Research methodology

Time series depending on the nature of the time parameter are divided into interval and momentary. When assessing the availability of natural moisture in the territory, we deal with interval series in which the value of the indicator is calculated for certain periods of time. These series correspond to flow variables. It should be noted that a series whose levels are the result of an integral series, starting from a certain defined level, is considered momentary.

In our research, we will assess the moisture availability of the territory by the amount of precipitation, complex climatic indicator, water consumption deficit and moisture reserves. All these criteria for assessing the natural moisture availability of the territory will be determined for the growing and/or critical periods of crop development.

The initial data will be meteorological data on average, maximum and minimum air temperature (^0C); atmospheric pressure at sea level (hPa); average relative humidity (%); daily precipitation (mm), air humidity deficit and average wind speed (km/h). This paper presents studies based on data from the Dnipro meteorological station (airport) for winter wheat. Meteorological data were taken from [20].

The amount of precipitation to assess the moisture conditions is calculated by accumulating their daily values for the corresponding period.

The complex climate indicator is calculated according to the recommendations set out in [4–6].

It is difficult to determine evapotranspiration in the field accurately, so it is usually calculated using empirical and semi-empirical equations. Some of them can be applied only in specific climatic conditions and cannot be used for other conditions and territories. Given that the Penman-Monteyn method is considered to be the standard method in the world, we will use it in our research.

Numerous computer programs have been created to determine ET_0 by the Penman-Monteith method. The Food and Agriculture Organization of the United Nations (FAO) recommends using the CROPWAT 8.0 program. However, the existing databases of this program (CLIMWAT, FAOCLIM) should be checked for compliance with real data and missing climatic parameters in certain periods of time. In addition, they contain only average monthly data, and there is no data on meteorological factors, soil and agroclimatic conditions and genotypic characteristics of crops grown in Ukraine. Therefore, the use of this program for the study area is impossible.

Considering the above-mentioned findings, it is advisable to use meteorological data measured at the meteorological station in the studies of natural moisture availability of the territory. Since the reference evapotranspiration (ET_0) is an indicator of climate impact, it is advisable to adopt it as a criterion for assessing the moisture availability of crops.

To calculate evapotranspiration (ET_0) we use the ET_0 Calculator Version 3.2 [21].

The choice of the year of a given availability is usually made on the basis of a retrospective series of years by ranking and determining the value of the exceedance probability. The disadvantage of this method is that the same number of years is attributed to each group of years by moisture conditions, and this is not true. After all, any series of observations contains a different number of years by moisture conditions. This drawback can be overcome by using methods based on artificial neural networks.

The analysis of the obtained results will be carried out by mathematical-statistical and cluster methods. The cluster method is used to solve the problem of classification of data obtained as a result of calculations. In addition, cluster analysis, unlike most mathematical and statistical methods, allows the distribution not by one parameter, but by several, and allows us to consider a set of input data of almost arbitrary nature.

The number of clusters is usually taken from 4 to 9 – 2-3 clusters are uninformative, and more than ten clusters are difficult to process. Therefore, in our studies, we take five clusters, each of which characterizes the moisture conditions of the year by the probability of exceeding (availability p, %): 0-20% – very wet, 20-40% – wet, 40-60% – average, 60-80% – dry, 80-100% – very dry.

Statistical multivariate cluster analysis of moisture availability of the study area will be conducted using Kohonen networks. The advantage of the network is that it is able to function in the face of interference, because the number of classes is fixed, the weights are modified slowly, and the adjustment of weights ends after training. It should be remembered that Kohonen maps offer only hypotheses about the cluster structure of the data. Therefore, for each cluster, its meaningful interpretation will be carried out using mathematical and statistical methods.

The distance to the center of the cluster is used as a criterion for the correspondence of a certain year to the humidity conditions of the territory. In this aspect, the scale becomes crucial in cluster analysis, because due to the heterogeneity of the features measurement units it becomes impossible to correctly calculate the distances between points. This problem is solved by preliminary standardization of variables.

To process the obtained calculations, the computer programs Mathcad and Deductor Studio were used [22].

4. Results and discussion

The table 1 shows the data on the calculation of the probability of exceedance separately for each of the adopted criteria using the mathematical and statistical method. To do this, the retrospective series were ranked separately for each criterion, and then the security of each member of the ranked series was calculated.

The analysis of table 1 shows that when choosing a year of a certain availability according to different criteria, the calculated real years, which characterize the moisture conditions of the

Table 1. Provision of the year by natural moisture of winter wheat crops.

Year	BCC	Year	ETo, mm/day	Year	P, mm	Year	W_{100}, mm	p, %	Humidification conditions
2021	0.938	2002	180.7	2014	286	2021	269.5	4.17	very wet
2001	0.863	2004	182.8	2021	285	2004	264.1	8.33	(p = 0-20%)
2004	0.820	2001	183.1	2004	253	2006	261.0	12.50	–
2014	0.776	2021	196.0	2001	241	2016	259.0	16.67	–
2016	0.720	2000	203.4	2016	219	2008	250.8	20.83	moist
2006	0.702	2022	204.6	2015	169	2001	250.4	25.00	(p=21-40%)
2015	0.702	2003	206.4	2011	168	2010	249.3	29.17	–
2008	0.677	2006	206.7	2017	158	2015	249.0	33.33	–
2011	0.571	2015	207.3	2000	155	2014	245.4	37.50	–
2017	0.559	2008	207.4	2008	155	2005	241.0	41.67	average
2005	0.516	2020	207.8	2006	150	2011	238.7	45.83	(p=40 – 60%)
2000	0.503	2017	210.0	2005	140	2000	238.7	50.00	–
2010	0.460	2016	211.1	2010	136	2002	237.9	54.17	–
2020	0.410	2014	213.9	2020	126	2017	237.4	58.33	–
2022	0.329	2005	222.2	2022	106	2018	233.1	62.50	medium dry
2019	0.292	2009	224.5	2019	103	2009	232.5	66.67	(p = 60-80 %)
2003	0.248	2011	227.1	2018	99	2019	229.2	70.83	–
2002	0.180	2010	228.8	2007	94	2022	226.6	75.00	–
2007	0.180	2019	234.2	2012	92	2003	220.2	79.17	–
2009	0.174	2007	237.8	2003	87	2013	217.4	83.33	dry
2012	0.149	2018	239.2	2009	72	2012	209.2	87.50	(p=80-100 %)
2018	0.118	2013	249.1	2002	65	2020	207.8	91.67	–
2013	0.112	2012	252.3	2013	55	2007	191.6	95.83	–

year by the probability of exceeding, do not coincide.

Thus, there is no clear answer as to which of the years should be taken as a model year. Therefore, in order to minimize internal differences between the evaluation criteria in each of the 5 groups that characterize the moisture conditions of the year by the probability of exceeding (provision p, %) and at the same time maximize the differences between the groups, we will use the cluster analysis method for the data presented in table 1.

The table 2 shows the main result of the cluster analysis in the form of a cluster number and a list of years belonging to each cluster. As additional information, the table contains the distance from the object to the center of the cluster. It will help to understand which of the years most closely corresponds to the moisture conditions.

The analysis of table 2 shows that the number of years in the clusters is different. Therefore, the determination of the probability of exceedance (p, %) by the conventional ranking is illegal.

Thus, the assessment of moisture conditions of the year can be carried out not by the quantitative criterion, but by the qualitative one. Since during the cluster analysis the entire retrospective series was divided into 5 clusters, the probability of exceeding (p, %) of each cluster can be estimated as the average of the established limits.

To visualize the data in table 2, we use Kohonen maps (Self-Organizing Map, SOM) (figure 2). The principle of building Kohonen maps is that in the process of training the model, neurons on the Kohonen map compete with each other for the right to best match the input data. This principle of competition and matching allows you to create a map that reflects the data structure of the original space in a lower-dimensional space. This facilitates further data analysis

Table 2. Distribution of years by moisture conditions into clusters.

Year	Cluster number	Distance to the cluster center	Humidification conditions
2001	0	0.2605	very wet
2004	0	0.2571	(p = 0-20%)
2014	0	0.2356	-
2016	0	0.2297	-
2021	0	0.2773	-
2000	1	0.1991	moist
2006	1	0.1974	(p=21-40%)
2008	1	0.0773	-
2015	1	0.0773	-
2017	1	0.1539	-
2007	2	0.3663	average
2009	2	0.2313	(p=41-60%)
2012	2	0.2677	-
2013	2	0.2375	-
2013	2	0.1960	-
2019	2	0.1927	-
2002	3	0.4593	medium dry
2003	3	0.1237	(p=61-80 %)
2020	3	0.2255	-
2022	3	0.0624	-
2005	4	0.0500	dry
2010	4	0.1147	(p=81-100%)
2011	4	0.1494	−

and visualization. The process of building a Kohonen map can be reduced to the following main stages: initialization; model training; successive iterations; end of training and mapping itself.

To evaluate the accuracy of Kohonen mapping, the mapping error is used as a metric. It occurs when SOM is trained on a large data set. This error measures the distance between the values obtained by SOM and the actual data values. Kohonen maps are considered to be highly accurate if this error does not exceed 0.1. In our research, we used the Deductor 5.3 analytical platform to build the Kohonen map and found an error of 0.01.

The analysis of figure 2 shows that the size of the clusters is different and the years are not evenly spaced. The cluster size is defined by its radius or standard deviation of the year for a particular cluster. A year belongs to a cluster if the distance from the location of the year in the cluster to the center of the cluster is less than its radius. In cases where this condition is met for two or more clusters, the year is controversial, that is, according to some of the selected criteria it can be attributed to several clusters. Therefore, in order to eliminate such ambiguities, the final choice of the year characterizing the established moisture conditions is made by the distance to the cluster center.

Consequently, the year with the minimum distance to the cluster cent is taken as the model year. In the calculations presented in this paper, we assume that for winter wheat a very wet year is 2016, a wet year is 2008, an average year is 2019, an average dry year is 2003, and a dry year is 2005.

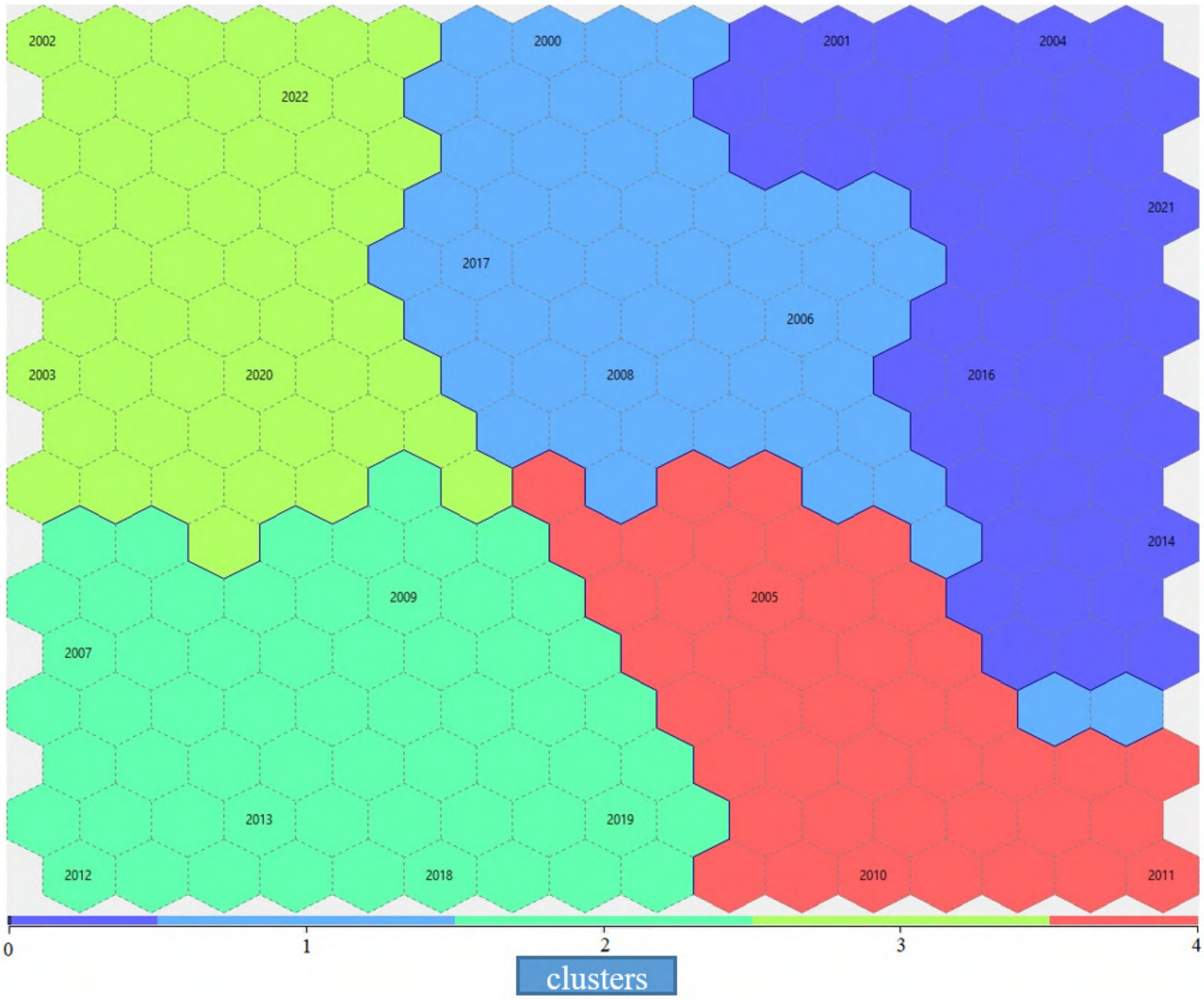

Figure 2. Distribution of years in clusters.

5. Conclusions

The data shown in table 1, table 2 and figure 2 indicate that when assessing the natural conditions of the territory based on hydrometeorological data, the cluster analysis method has significant advantages over the statistical one, as it gives a clear answer to which of the available retrospective years most accurately characterizes the moisture conditions of the territory. This is due to the consideration of several criteria. Assessment of natural moisture availability of the territory by several criteria allows to characterize the dynamics and intensity of changes in hydromelioration factors during the growing season of crops.

In the context of global climate change, the problem of availability and use of water resources is exacerbated, and the use of the proposed methodology for determining the moisture availability of the territory makes it possible to more accurately determine the need for water during hydro-amelioration measures. That is why it is advisable to choose the calculation year according to several criteria using the cluster analysis method.

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References

[1] Romashchenko M, Yatsyuk M, Zhovtonog O, Dekhtiar O, Saydak R and T M 2017 *Land Reclamation and Water Management* **106** 9–14 ISSN 2616-5643, 2616-5562 URL http://nbuv.gov.ua/UJRN/Mivg_2017_106_4

[2] Lebedev A M 1959 *Trudy Glavnoi Geofizicheskoi Observatorii* **115** 3–48

[3] Polovyi A M, Bozhko L I and Volvach O V 2012 *Osnovy ahrometeorolohii* (Odesa: TEC)

[4] Okopnyi O I 1997 *Assessment and forecast of the influence of climatic and meliorational factors on the water regime of drained lands* Ph.D. thesis Ukrainian State Academy of Water Management Rivne 05.20.05

[5] Rokochynskyi A M, Okopnyi O I and Zubyk Y I 1996 *Evaluation and forecasting of meteorological values in vegetation periods characterized by moisture conditions for water balance calculations and agrometeorological forecasts on a long-term basis: Methodological guidelines* (Rivne: Ukrainian State Academy of Water Management)

[6] Rokochynskyi A M, Okopnyi O I and Zubyk Y I 2010 *Scientific and practical aspects of optimization of water regulation of drained lands on ecological and economic grounds* (Rivne: The National University of Water and Environmental Engineering)

[7] Rokochinsky A M, Turchenyuk V O, Volk P P, Koptyuk R M, Velychko S V, Prykhodko N V, Frolenkova N A and Volk L R 2020 *Automation of design and calculations of water management and reclamation facilities* (Rivne: The National University of Water and Environmental Engineering) ISBN 978-966-327-478-2 URL https://ep3.nuwm.edu.ua/19770/

[8] Alpatiev A M 1969 *Moisture cycles in nature and their transformations* (Leningrad: Gidrometeoizdat)

[9] Alpatiev S M 1965 On irrigation regimes of agricultural crops *Irrigated agriculture in the European part of the USSR* pp 185–190

[10] Ostapchik V P 1989 *Information-advising irrigation management system* (Kiev: Urozhai)

[11] Shtoiko D A, Pysarenko V A, Bychko O S and Yelazhenko L I 1977 *Irrigated agriculture* **22** 3–11

[12] Penman H L 1956 *Netherlands Journal of Agricultural Science* **4**(1) 9–29 ISSN 0028-2928 URL https://doi.org/10.18174/njas.v4i1.17768

[13] Blaney H F and Criddle W D 1950 *Determining water requirements in irrigated areas from climatological and irrigation data* (Washington, D.C.: U.S. Soil Conservation Service) URL https://ia800300.us.archive.org/4/items/determiningwater96blan/determiningwater96blan.pdf

[14] Allan R G, Pereira L S, Raes D and Smith M 1998 Crop evapotranspiration - Guidelines for computing crop water requirements FAO Irrigation and drainage paper 56 FAO - Food and Agriculture Organization of the United Nations Rome URL https://www.fao.org/3/X0490E/x0490e00.htm

[15] Hanson B 2011 Crop Coefficients URL http://web.archive.org/web/20220907054429if_/https://ucanr.edu/sites/irrigation_and_soils_/files/93370.pdf

[16] Allen R 2010 Penman-Monteith Evapotranspiration Calculations: Reference ET and Crop Coefficients *ET Workshop: Using the Best Science to Estimate Consumptive Use - CoAgMET* URL https://coagmet.colostate.edu/ET_Workshop/pdf/2_Allen.pdf

[17] Sumner D M and Jacobs J M 2005 *Journal of Hydrology* **308**(1-5) 81–104 URL https://doi.org/10.1016/j.jhydrol.2004.10.023

[18] Farg E, Arafat S, Abd El-Wahed M and EL-Gindy A 2012 *The Egyptian Journal of Remote Sensing and Space Science* **15**(1) 83–89 ISSN 1110-9823 URL https://doi.org/10.1016/j.ejrs.2012.02.001

[19] Litovchenko A F 2011 *Agrohydrometeorological calculation method soil moisture and water-saving modes of moistening of irrigated crops in the Steppe and Forest-Steppe of Ukraine* (Dnepropetrovsk: Svidler A.L.)

[20] Tutiempo Network, SL 2023 Clima en DNIPROPETROVSK - Históricos el tiempo (345040) URL https://www.tutiempo.net/clima/ws-345040.html

[21] 2012 ETo Calculator URL https://www.fao.org/land-water/databases-and-software/eto-calculator/en/

[22] PTC Inc 2023 Mathcad: Math Software for Engineering Calculations URL https://www.mathcad.com/en

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The current state of the Southern Bug River mouth ecosystem

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The current state of the Southern Bug River mouth ecosystem

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Abstract. The article considers the pre-war conditions main components of the Southern Bug mouth ecosystem. The results of sediments samples study have shown transformation of lagoonal accumulation, appearance of reducing condition spots in sediments, presence of exceeding MAP for lead. An estuarine water analysis given an idea about hydrochemical features mouth section of river, namely: high concentration of suspended solids – on an average 11,4 mg/dm^3; increasable concentration BOD$_5$ – an indicator of easily oxidized organic substances content; periodic significant exceeding MAC of ammonium and nitrite nitrogen. Hydrobiological changes primarily concern a decrease in primary productivity due to a decline in phytoplankton biodiversity; there was also a reduction of zooplankton. The current state of the Southern Bug River mouth ecosystem is formed predominantly under the periodic dredging of shipping channels followed by the formation silt dumps. The post-war revitalization of the Southern Bug estuary ecosystem should include measures to mitigate the negative effects of anthropogenic activity especially the consequences of hydraulic engineering works.

1. Introduction

The Southern Bug is one of the largest rivers of Ukraine, which constantly experiences significant anthropogenic pressure due to the high regulation of the river, large-scale ploughing of coastal areas, dense settlement load. At the same time, the Southern Bug plays a very essential economic and social role in the functioning of the Black Sea region of Ukraine – it is a transport artery, a source of drinking water and food, a place of recreation, etc. If you look at this range of ecosystem services, especially in the context of global climate change, it is impossible to overestimate the importance of the Southern Bug River in the socio-economic development of the southern part of Ukraine [1]. However, now, since the beginning Russia's full-fledged military aggression, the territory the Southern Bug River mouth is under catastrophic influence due to bombing and shelling.

The current state of the Southern Bug mouth ecosystem is formed under the influence of the multi-purpose usage of the river; one of the most powerful factors affecting the estuary part of the river is shipping and the associated periodic dredging of shipping channels. The Bug-Dnipro-estuary Canal (BDEC) serves as the entrance for the ships to Mykolaiv Port and a number of ports in the estuary. In addition, the lower part of the Southern Bug is intensively used for economic purposes: hydrotechnical (water intakes, discharges), fisheries, irrigation, etc. [2]. Periodic hydrotechnical dredging measures have a significant impact on the functional capacity of the river ecosystem and its biota.

The key goal of the presented research was to characterize the pre-war state of the Southern Bug River mouth ecosystem using a wide range of indicators, including lithological, hydrochemical and hydrobiological ones.

In order to achieve the above goal, expeditionary research of the Southern Bug River mouth, laboratory and desktop processing of the results was carried out. Moreover, comparative assessment of the obtained results with the results of own previous research and literature data was fulfilled; the features of the obtained indicators in the context of anthropogenic activity are characterized and possible ways of mitigating environmental problems are considered.

2. Materials and methods

The presented materials are based on the research data of the Southern Bug lower part in the spring and summer of 2021, analysis of research data of 2012 and analysis of literature. The research area is the Southern Bug River mouth, which is part of the Dnieper-Bug estuary (figure 1).

Figure 1. The research area.

The study of modern sediments of the lower part of the Southern Bug River has been carried out. The sampling points were located along profiles that crossed an investigation object. We researched samples from two profiles: first – near the port Olvia, second – across the Southern Bug (between villages Parutyne – Lymany).

The Southern Bug River research area was conducted at the lower reaches, below the Mykolaiv city; 18 samples of sediment and 27 samples of water were selected. Samples of sediments were taken with the special cylindrical equipment. The thickness of the sediment layer selected for analysis was 0.1–0.25 m. After drying, the selected samples were subjected to averaging at the points of selection.

The sediment samples analysis included the description of sediments, determination of their granulometric composition and density; definition of physical and chemical indicators: pH, Eh, electrical conductivity. The chemical composition study of the samples consisted in the pollutant elements determination, the water-soluble salts content and iron oxides.

The water samples analysis included the determination of the chemical indicators, namely: pH, total salts, dissolved oxygen, suspended substances, chlorides, sulphates, biological oxygen consumption (BOD_5), the content of ammonium, nitrite, nitrate and total phosphorus. All indicators in the water were determined by standard methods.

Hydrobiological studies consisted in general assessments of phytoplankton and phytobenthos, zooplankton and zoobenthos, and characterization of higher aquatic vegetation involved. The samples of phytoplankton were taken and processed through standard hydrobiological procedures [3,4]. Both qualitative and quantitative characteristics of phytoplankton in performing ecological analysis were used.

3. Results

The modern sediments of the mouth Southern Bug River mouth represent mainly silt. Sands develop in some places in the form of narrow coastal strips, as well as on beaches and capes. Shell rocks occur in the form of small spots on beaches and spits that cannot be mapped.

Due to the solid runoff from the Southern Bug River, estuarine deposits are covered with a thin layer of modern sediments in the Dnieper-Bug estuary, in the Bug part area of the shipping channel and the water areas of the ports. The role of solid runoff from the Southern Bug River and the Inhul River is small in the formation of depth topography and silting of the shipping channels of the Dnieper-Bug estuary. The origin of sandy coastal strips and spits does not depend so much on the flow of rivers, with the erosion of the shores composed of fine sand. The maximum discharge of suspended sediments is observed at the rise of the spring flood, the minimum – during the winter low tide.

Extracted sediment, which is picked up due to permanent dredging works in the Southern Bug River mouth is transported to local soil dumps, where it forms continuous silt deposits. Sediments of the Southern Bug mouth, at the present stage, along the route of the Bug-Dnieper-estuary Canal (BDEC) are represented by: sandy silts with inclusions of fine sand, loamy silts, flowing clay silts [5].

The results of the sediments granulometric composition of the Southern Bug River mouth testify to the transformation of lagoonal sediment accumulation (table 1, figure 2). The data obtained from the Parutyne – Lymany profile shows a predominance of psammite. While the material taken upstream (in the area of the port of Olvia) has a siltstone-psammite composition of the samples near the shore and a pelitic composition in the central part of the river, in the direction of the Bug-Dnieper-estuary Canal.

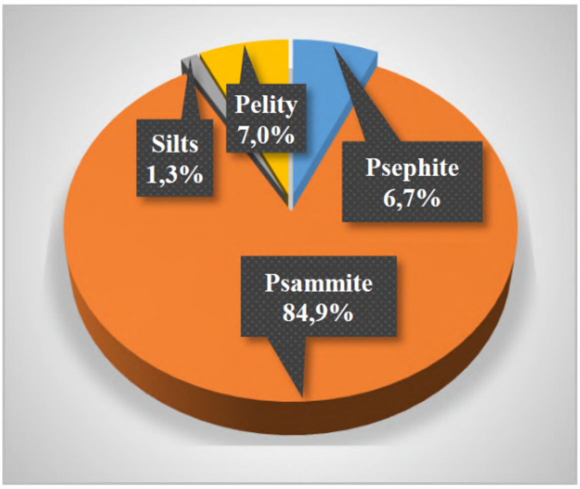
The data listed in Table 1 shows a significant variation in grain size and at the same time make it possible to identify a tendency to the increase of pelitic fraction in sediments. Areas along the shipping channel have sediments represented mainly by pelity. Finely dispersed material is constantly stirred by ships and dispersed over a long distance. In addition, shipping channel sections contain a large amount of industrial waste.

Technogenic sediments are widely developed in the studied area. Moreover, they are most widespread in the coastal part of the land and much smaller in open water areas. In the water area, the Southern Bug mouth man-made formations were discovered by a number of drilling wells in the form of different area spots, mostly not far from the ports. In the water area of the estuary, the fields of technogenic sediments occur near landfills of raised soil from the estuary depth during passage, deepening and periodic cleaning of shipping channels, capital dredging and during other dredging works [5].

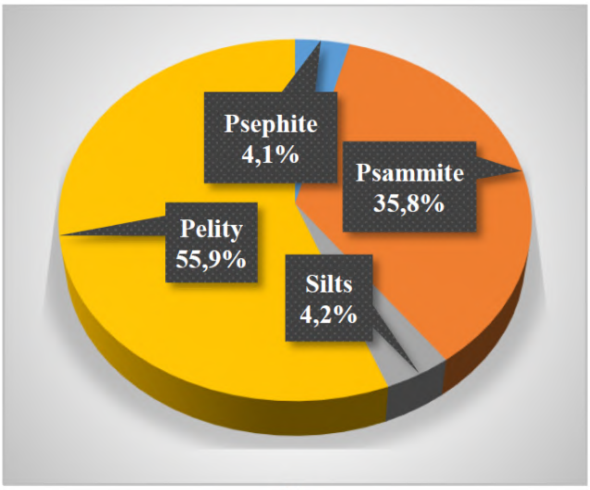
Bottom soil, during research in 2021, was characterized by thick creamy consistency of almost black colour in the area of the port of Olvia with a noticeable smell of hydrogen sulphide in two plots. In the area of the Parutyne – Lymany profile, the sediments were brown with black

Table 1. Granulometric composition of the sediments, %.

Sampling locations	Particle size fractions			
	Psephite, (>2 mm)	Psammite, (2–0.1 mm)	Silts, (0.1–0.05 mm)	Pelity, (<0.05 mm)
Parutyne – Lymany profile				
Point 1	5.10	92.08	0.87	1.95
Point 2	17.24	82.29	0.47	0.00
Point 3	10.13	71.06	1.40	17.40
Point 4	1.42	94.86	2.17	1.55
Point 5	5.66	93.82	0.52	0.00
Point 6	0.74	75.24	2.65	21.36
Port Olvia profile				
Point 1	0.63	61.95	11.10	26.32
Point 2	1.72	56.49	5.77	36.02
Point 3	2.60	9.30	0.00	88.10
Point 4	11.40	15.60	0.00	73.00



a)



b)

Figure 2. Granulometric composition of the Southern Bug River sediments: a) Parutyne – Lymany profile; b) port Olvia profile.

interspersed and had a weak marine smell.

According to the research results, the density of the sediment in the Parutyne – Lymany profile varied from 2.23 to 2.47 g/cm^3; the density of the port Olvia profile sediment was lower and ranged from 1.52 to 1.69 g/cm^3. Density indicators of sediment samples correlate strongly with its particle size composition.

Chemical analysis of sediment samples made it possible to obtain the following data on chemical elements-pollutants (table 2). Research results show that with the exception of one sample, the content of elements-pollutants in all profile‘s samples did not exceed the MAC for soils.

Table 2. Chemical analysis of sediment samples in the profile port Olvia.

Indicator	Sampling points, M±m, mg/kg			
	Point 1	Point 2	Point 3	Point 4
As	1.95±0.33	1.74±0.37	0.88±0.29	1.05±0.31
Pb	34.0±8.91*	4.0±1.05	2.0±1.45	10.0±3.0
Cd	0.33±0.09	0.24±0.08	0.28±0.09	0.29±0.09
Cr	15.0±3.28	12.0±3.12	1.0±0.28	2.0±0.29
Cu	10.0±3.12	6.0±1.17	3.0±0.95	2.0±0.89
Ni	0.7412.0±4.51	8.0±2.84	1.0±0.34	1.0±0.27
Zn	31.0±7.14	18.0±3.96	6.0±2.14	5.0±2.11
Hg	<0.07	<0.07	<0.07	<0.07
Fe	7740.0±986.52	5870.0±857.15	567.0±96.25	973.0±89.44
Mn	85.0±24.31	116.0±24.68	24.0±6.47	60.0±14.95

* – exceeding the maximum allowable concentration (MAC) of soils

Comparing the data obtained by us with the data given in [5], we can note that the data on cadmium and lead are within the measurement error limits and are comparable (table 3), while the composition of zinc and copper in our studies is on average 10 times lower.

Table 3. Concentration of chemical pollutants in the sediments samples BDEC knees (July-August 2018) [5].

Indicator	Unit of measurement	Sampling points, knees BDEC					
		6	7	8	9	10	11
Cd	mg/kg	0.165	0.390	0.264	0.257	2.64	0.336
Pb	mg/kg	14.2	23.3	13.3	9.3	17.0	7.53
Zn	mg/kg	70.9	101.0	68.8	75.3	140.0	64.1
Cu	mg/kg	16.5	26.5	35.1	24.5	34.3	25.0

The values of physical and chemical parameters of the current sediments of the studied profiles are shown in table 4.

Table 4. Physical and chemical parameters of the sediments.

Sampling locations	Concentration of water-soluble salts, % in 100 g of dry sample	pH (Units)	EC (mkSm/cm)	Eh (mV)	k (Fe_2O_3/FeO)
Parutyne – Lymany profile	0.157	7.14 – 7.62	0.45	+85.0 – +175.0	1.77 [6]
Port Olvia profile	0.875	6.45 – 6.95	1.95	-105.0 – +105.0	0.90

It should be noted that the content of water-soluble salts in the sediments depends on their sorption capacity, which, in turn, depends on the grain composition of the sediments. Accordingly, finely dispersed sediment (especially in dumping areas) has a greater sorption capacity and is more saline. However, of course, water salinity determines the content of water-soluble salts in the sediments. The salinity of the water at the Southern Bug mouth is on average 2.3–3.5‰, the maximum being 10–11‰. During the period of spring observations, water salinity in the area Parutyne – Lymany profile was 3.5‰, and the port Olvia profile was 3.1‰.

Mixing of two different waters: fresh river water and salty seawaters play a special role in the formation of the hydrochemical regime of the Dnieper-Bug estuary water. Fresh river water and salty seawaters determine the special chemical composition of the water of the Southern Bug mouth. However, the main source of biogenic substances entering the river is river runoff, hydrobionts, sediments and wastewater.

The indicator of the acid-base state (pH) of the water in the Southern Bug mouth is quite variable and ranges from 6.9 to 8.9 units, depending on the growing season. Most hydrobionts can usually tolerate a pH range of 5 to 9. Nevertheless, the change in pH to the alkaline side, which is observed during the "water bloom", can lead to an increase in free ammonia in the water, into which ammonium ions pass because of the increase in pH. Both ammonium ions and ammonia can be present in water within pH 8–9.

An important factor influencing the process of forming a chemogenic and biogenic complex of bottom sediments is the saturation of the water object with oxygen. Bottom sediments of natural water flow relate to the balanced aerobic-anaerobic system type. However, there are the shifts of aerobic-anaerobic balance toward anaerobic, which, in its turn, leads to the formation of another chemogenic complex and partial or total destruction of conventional ecotypes. One of the indicators of aerobic-anaerobic shift in balance toward reduction can be displacement of the ratio in the bottom sediments of iron oxides, namely the predominance of FeO over Fe_2O_3. In a number of works [6–8], the dynamics of accumulation and distribution features of a number of metals, including iron oxides, in river sediments have been analysed. The authors note that with the increase in the volume of organic matter runoff, whose rate of biodegradation does not keep up with the rate of its arrival, the development of anaerobic conditions is possible, which is reflected in the ratio of metal oxides.

Determining the ratio k (Fe_2O_3/FeO) shows fluctuations in river redox conditions. In the bottom layer of Parutyne – Lymany profile k (Fe_2O_3/FeO)>1, therefore the oxidation-reduction conditions can be defined as transient with a non-constant aerobic-anaerobic balance or oxidative. While in the Port Olvia profile in the bottom layer k (Fe_2O_3/FeO)<1 on average, indicating the formation reducing conditions.

Thus, the study has shown that there is recently been a general tendency to silting rivers, especially in their lower reaches. This leads to a shift in the natural aerobic-anaerobic balance to the reducing side, which negatively affects the hydroecosystem in general. An indicator of this process can be the ratio of iron oxides (k Fe_2O_3/FeO) and the value <1 [6].

The average concentration of dissolved oxygen in water during the research period was at the level of 5.1 mg O_2/dm^3. However, the values of this indicator differed significantly: in the surface water – in the range of 6.5 – 8.0 mg O_2/dm^3 and in the bottom layer – 0–3.5 mg O_2/dm^3. In the profile Parutyne – Lymany, the oxygen content was higher than in the profile of the port of Olvia. At two sites in the port Olvia profile, oxygen in the bottom layer of water was not determined, and Eh of the sediment had negative values.

Relating our data to the information provided by the Laboratory of Analytical Control of the State Administration of Ecological Resources in Vinnytsia Oblast, we can note that the data are comparable. So, the water quality in the Southern Bug River in 2003–2008, was characterized with the satisfactory oxygen regime (the content of dissolved oxygen was within the range of 7.1 to 10.8 mg O_2/dm^3 [2]; water hardness average being 3.6–8.0 mg-eq/dm^3.

The concentration of total phosphorus, according to our research, in the water area of the port

Olvia profile varied in the range of 1.4–3.2 mg/dm^3; ammonium nitrogen – 0.1–0.25 mg/dm^3; nitrate concentration was determined within the range of 11.0–14.3 mg/dm^3; the nitrite content being 0.005–0.04 mg/dm^3.

The degree of surface waters pollution in Ukraine is regulated by the established maximum allowable concentrations (MAC). Most of the standards were approved during the Soviet era, and have since then expired. However, new standards have not yet been adopted in Ukraine, so State sanitary rules 4630-88 dated 04.07.1988 are used for comparisons. According to the state sanitary rules, the presented indicators of nitrogen content do not exceed the norms.

The turbidity and colour of the water depend on many factors and fluctuate significantly in the estuary of the Southern Bug throughout the year. The main natural factors of water turbidity are the amount of solid runoff and the mass of phytoplankton (especially the development of microalgae in the summer months). However, significant turbidity in certain areas is caused by anthropogenic factors: dredging, shipping and dumping. Thus, the concentration of suspended particles in the port Olvia profile water that we measured, ranged from 7.6 to 12.6 mg/dm^3 (under the conditions of the MAC of 0.75 mg/dm^3). According to [5], during the operation of a dredger, the water turbidity can reach 70 mg/dm^3 and spread in the radius of 50 to 150 m, depending on the speed of the current. Undoubtedly, the decrease in water transparency is reflected at all levels of the trophic chain of the hydroecosystem.

Determination of biological oxygen demand (BOD_5) – is an indicator that characterizes the content of easily oxidized organic substances pollutants, contained in water – confirmed the differences between the profiles. If in the area port Olvia profile this indicator did not exceed the MAC and fluctuated in the range of 2.3–3.1 mg O_2/dm^3, then in the area of Parutyne – Lymany profile the values of this indicator were on average twice higher – 4.7–8.2 mg O_2/dm^3, which in some places exceeds the MAC by one and a half times. Comparison of this indicator with [2] resulted in same data. So, pollution with organic compounds observed (biological oxygen demand (BOD_5) fluctuated within the range of 2.11–5.4 mg O_2/dm^3.

The concentration of sulphates in the water slightly exceeded the MAC in the port Olvia profile. Thus, we determined sulphate concentrations within the range of 502.5 – 532.5 mg/dm^3. In the area of the Parutino-Lymany profile, on the contrary, the concentration of sulphates was lower, it did not exceed the MAC, and amounted to 315.0 – 340.5 mg/dm^3. The chloride content was high and was determined at the level of 3047.0 – 3244.0 mg/dm^3. This is definitely higher than the MAC, however, the chloride concentration is mainly determined by the inflow of seawater.

In general, the hydrochemical parameters of the Southern Bug mouth water in the studied period did not differ from the average long-term values. The most threatening situation is with significant turbidity of the water and extremely low oxygen concentration in some places.

A key goal presented in aquatic biology studies is to introduce data characterizing the status of the aquatic environment with a broad range of measurable indicators including in-stream habitat, phytoplankton, zooplankton, macroinvertebrate and macrophyte assemblages.

The area of the Southern Bug mouth is a transition zone – the continuum between freshwaters and coastal marine waters. According to the EU Water Framework Directive (The Directive 2000/60/EC) are defined as "bodies of surface water in the vicinity of river mouths which are partially saline in character as a result of their proximity to coastal waters but which are substantially influenced by freshwater flows". The salinity is a major, if not the most important, natural factor structuring the algal communities and explaining their variability within these ecosystems [9–11]. Furthermore, transitional waters have intrinsically higher productivity in comparison to open seawaters. This may be attributed to the fact that such zones are deemed to be naturally stressed systems as they work as basins for runoff from their catchments and impact of saline waters from the sea [12]. Thus, in the water area of the Southern Bug low reaches (below the city of Mykolaiv), a transitional community is formed, consisting of freshwater and marine species that are on the edge of their ecological ranges.

The phytoplankton community composition of the Southern Bug estuary system fluctuates from 50 to 60 species in the context of average long-term indicators (over the past 15 years), which are represented mainly by cyanobacteria, diatoms and green algae [13, 14]. Diatoms (*Chromista, Bacallariophyta*) have a wide range of interesting morphological and physiological features and are the main component of marine and freshwater ecosystems [15]. The majority of centric diatoms genera are discovered in strictly marine waters but in freshwater environments, this group is present with much less diversity [16].

The transitional zone of the Mykolaiv area with its changing salinities is offering conditions for the existence of 24 centric diatom taxa representing 11 genera. Species-indicators of eutrophication in the coastal zone of the Black Sea waters, which enter the estuary and then move upstream of the South Bug River, have been identified [17]. Thus, the following taxa are resistant to pollution by organic substances: *Aulacoseira subarctica, Cyclotella atomus, C. choctawhatcheeana, Cyclostephanos dubius, Melosira varians, Skeletonema subsalsum, Stephanodiscus hantzschii, S. Minutulus.*

Only taxa with high euryhalinity tolerance are able to move upstream and adapt to eutrophic freshwaters. The study [17] shows that salinity is one of the most significant factors for the species composition of diatoms. The appearance of three alien marine species (*Actinocyclus normanii, Skeletonema subsalsum, Thalassiosira incerta*) in the lower part of the Southern Bug might be considered as the immigration of marine species into this area due to change in salinity. Therefore, the monitoring of these species is important for biodiversity conservation.

At present, freshwater and euryhaline species prevail – up to 59%. The number of halophilic representatives of phytoplankton varies from season to season (which is associated with the upward of seawaters). The optimal water salinity for phytoplankton is 0.4–5.2 ‰.

In spring, cyanobacteria, diatoms and dinophytes predominate in phytoplankton. However, the biomass of phytoplankton in spring is low, up to 1.5 g/m^3. In summer, biomass of phytoplankton increase. Cyanobacteria play the dominant role in the formation of summer phytoplankton biomass. Many representatives of diatoms, dinophytes, and golden algae, contained in the phytoplankton of the study area are of little value in terms of nutrition. Their share in the formation of the total biomass of phytoplankton is 75%. During the vegetation period, the number of phytoplankton varies within the range of 600 – 261530 cells/m^3, and the biomass – within the range from 1.45 to 21.04 g/m^3. The smallest phytoplankton biomass is observed in dumping areas (storage of sediment after dredging). In the areas adjacent to the port under partially anaerobic conditions, the phytoplankton biomass is minimal.

The qualitative structure of cyanobacteria has not changed significantly in recent years, which indicates the stability of the hydrobiological situation. The dominant species are: *Aphanizomenon flos-aquae, Microcystis aeruginosa, Oscillatoria agardhii, Anabaena spiroides.* Among diatoms *Diatoma elongatum, Melosira granulata* and *Nitzchia tenuirostris* are most frequently registered. A group of protococcus dominated by *Scendesmus quadricauda* forms the basis of green algae. Vegetation of other groups of algae (euglenoid, dinophytic, golden, yellow-green) is determined at a much lower level. The dominant species are: *Euglena viridis, Cerratium hirundinella, Synura uvella.*

As a result of the intensive hydrotechnical construction of the previous century, the conditions for the existence of hydrobionts along the entire length of the Southern Bug River have changed significantly, which was inevitably reflected in the Bug estuary ecosystem. The researched area of the river is constantly under severe stress due to anthropogenic influence, the most important factor among which is water turbidity, which limits the photosynthetic activity of algae. These waters can be considered among the most affected and endangered ecosystems. Considering that, it is difficult to exclude these impacts on the species diversity of spatial and ecological gradual boundaries between the systems; nevertheless, salinity is believed to be a prevailing stressor [18, 19].

Studies of microphytobenthos have carried out upstream the city of Mykolaiv [20] show a much larger number and a greater variety of algae. Thus, data on the identification of 121 species of algae, which belong to 61 genera, 34 families, 20 orders, 6 classes and 5 divisions, are given. By the number of species, diatoms prevail (86 species or 71.07%), a much smaller number of representatives fall into the rest of the divisions. Thus, there are 20 species of green algae (16.52%), 9 species of cyanobacteria (7.43%), 3 species of euglena and chara (2.47% respectively).

The species diversity of zooplankton has almost halved over the past 30 years. At the end of the 1990-s 72 taxa were identified in zooplankton, while in the last 5 years only 36 species were identified in the water area of the Southern Bug mouth area. Wheel animalcules (*Rotifera*), copepods (*Copepoda*) and water fleas (*Cladocera*) form the main part of the zooplankton biomass. Freshwater and euryhaline forms dominate [13, 14, 21].

The number of zooplankton (average annual) does not exceed 18 th. specimens/m^3 and the biomass does not exceed 1.5 g/m^3. Among the representatives of zooplankton 40% are wheel animalcules. In spring, water fleas (up to 70%) represent the main biomass of zooplankton. The basis of the biomass of rotifers was formed by *Asplanchna priodonta*. However, the numbers were formed by smaller forms of *Filinia longiseta, Brachionus angularis, Keratella quadrata*.

The fauna of the depth (zoobenthos) and periphyton is more diverse and rich than the aquatic fauna. At the mouth of the Southern Bug River (study area), water exchange is slowed down and salinity is increased. Oligochaetes, polychaetes, gammarids and chironomids dominate in the silt and sandy-silt bottom areas. The biomass of summer zoobenthos of silted sands is up to 26 g/m^3. Among polychaetes *Hypaniola kowalewskii* and *Nereis diversicolor* dominate. Among gammarids *Pontogammarus robustoides* and *Dikerogammarus haemobaphus* are identified.

In some places, there are still small colonies of mollusks *Dreissena bugensis*, and along the spits (including the Northern Spit) there are mollusks *Cerastoderma edule*. Taxonomic diversity, abundance and biomass of zoobenthos of the Bug estuary are not the same in different areas. At great depths with increased salinity, low oxygen concentration and the presence (in some places) of hydrogen sulfide, the zoobenthos is taxonomically poor. Oligochaetes (24%), polychaetes (15%), molluscs (18%), and sometimes chironomids prevail in such areas not forming mass settlements.

Studies of higher aquatic plant in the mouth area of the Southern Bug River showed a depleted species composition of floristic communities [22], which form two plant complexes – coastal (helophytes) and aquatic (free-floating). The helophytes community, which is formed by border strips of different lengths and massiveness along the coastline, is represented mainly by reeds (*Phragmites australis*), in some places there are cattails (*Typha latifolia, Typha angustifolia*), sedges (*Carex acuta, C. raparia, C. gracilis*).

Mainly representatives of the genus *Potamogeton* qualify as aquatic vegetation, which forms "spots" of hydatophytes and floating pleistophytes in the water area, namely: *P. crispus, P. lucens, P. pillsum, P. natans, P. perfoliatus*. In addition, *Myriophyllum spicatum, Ceratophyllum demersum* are found in the water area.

4. Discussion

The specificity of the processes that take place in the Southern Bug River mouth is caused by the constant interaction of different physical and chemical properties of river and seawaters masses. The upward-downward fluctuations of water levels are a characteristic feature of the hydrological regime of the Bug estuary system. Getting through the flume of the navigable canal to the Bug estuary seawater stagnates due to very slow water exchange at the bottom. Seawater moves in the south winds and it is a constant source of increasing salinity at the mouth of the river, which fluctuates between 2–3.5‰ for most of the year.

Another feature of the Southern Bug mouth water is its considerable turbidity. Anthropogenic activity is the main cause of high concentration of suspended particles in the water. It is provoked by permanent dredging works in the Southern Bug River mouth and transporting material to local soil dumps. In 2021, the average content of suspended solids in water in the profiles below the city of Mykolaiv were 11.4 ± 0.5 mg/dm^3.

Current sediments of the Southern Bug mouth reflect to transformation of lagoonal sediment accumulation. The role of sediment runoff from the Southern Bug River and the Inhul River in the formation of the bottom relief and siltation is insignificant. The current sediment of the Southern Bug mouth is mainly represented by pelity.

The content of pollutant elements in the sediment samples mostly does not exceed the MAC, except for lead in one sample. However, in our opinion, the presence of reducing conditions in river's bottom layers fixed some samples is much more important is a great concern.

Permanent turbidity of water leads to a decrease in the photosynthetic activity of phytoplankton, which in turn is reflected in reduced primary production. Other hydrochemical indicators, that periodically have increasable concentration in the Southern Bug mouth water, include: BOD_5, which is characterized by periodic, sometimes significant, exceeding of MAC, ammonium and nitrite nitrogen.

Very often, transitional water is a place with increased biodiversity as the estuarine community consists of both freshwater and marine species. The Southern Bug mouth waters are considered to be among the most affected and endangered ecosystems. According to the literature review, decrease in primary productivity led to decrease in zooplankton almost by half. The composition of phytoplankton is dominated by representatives of diatoms, dinoflagellates and golden algae, which are of little value in terms of food, whose specific weight in the formation of the total biomass of phytoplankton is up to 75%.

Analysing all of the above, it should be noted that the post-war revitalization of the Southern Bug estuary ecosystem should include measures to mitigate the negative effects of anthropogenic activity, especially the consequences of hydraulic engineering works.

5. Consequences

The presented comprehensive research can be considered as the current pre-war state of the Southern Bug mouth ecosystem. The results of the conducted research are: assessment of the sediments features of the researched river section, assessed water conditions and characteristic of the groups of hydrobionts.

Appearance of reducing condition spots in sediments, increased turbidity, change of hydrochemical conditions, reducing of some fodder species (plankton and benthos) – these are short list of current anthropogenic transformation of Southern Bug mouth ecosystem.

The first and urgent measures to revitalize the mouth of the Southern Bug should be actions to eliminate and mitigate the consequences of hostilities. Further revitalization measures should be aimed at preserving biodiversity, which is possible under the conditions of maintaining the normal state of water and sediments in the Southern Bug, especially in the transitional estuarine zone.

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References

[1] Bezsonov Y, Krysinska D and Rossol R 2021 *Visnyk of V.N. Karazin Kharkiv National University, series "Geology. Geography. Ecology"* (54) 141–154 URL `https://doi.org/10.26565/2410-7360-2021-54-11`

[2] Radomska M M, Ryabchevsky O V, Vologzhanina V V and Kovalska V V 2018 *Environmental safety and natural resources* **27**(3) 92–102 URL `https://doi.org/10.32347/2411-4049.2018.3.92-102`

[3] Romanenko V D 2006 *Methods of hydroecological investigations of surface waters* (Kyiv: Logos Press)

[4] Topachevskiy A V and Masyuk N P 1984 *Freshwater algae of Ukraine* (Kyiv: Vyshcha Shkola)

[5] Synkevych 2021 Environmental impact assessment report of the planned activity "Reconstruction of the Bug-Dnieper-estuary Canal (BDEC). Mykolaiv region. Ensuring the safe movement of ships around the clock in one-way mode" Preprint Subsidiary "Delta-pilot" of the SE "Seaports Administration of Ukraine" Mykolaiv

[6] Alokhina T 2018 *Journal of the Belarusian State University. Ecology* (1) 24–29 URL `http://journals.bsu.by/index.php/ecology/issue/view/39`

[7] Miao S, DeLaune R and Jugsujinda A 2006 *Science of The Total Environment* **371**(1) 334–343 ISSN 0048-9697 URL `https://doi.org/10.1016/j.scitotenv.2006.07.027`

[8] Ramírez-Pérez A M, de Blas E and García-Gil S 2015 *Science of The Total Environment* **538** 317–326 ISSN 0048-9697 URL `https://doi.org/10.1016/j.scitotenv.2015.07.111`

[9] Cebrián J and Valiela I 1999 *Journal of Plankton Research* **21**(3) 429–444 ISSN 0142-7873 URL `https://doi.org/10.1093/plankt/21.3.429`

[10] Bode A, Álvarez Ossorio M T, González N, Lorenzo J, Rodríguez C, Varela M and Varela M M 2005 *Estuarine, Coastal and Shelf Science* **63**(1) 285–300 ISSN 0272-7714 URL `https://doi.org/10.1016/j.ecss.2004.11.021`

[11] Muylaert K, Sabbe K and Vyverman W 2009 *Estuarine, Coastal and Shelf Science* **82**(2) 335–340 ISSN 0272-7714 URL `https://doi.org/10.1016/j.ecss.2009.01.024`

[12] Zaldivar Comenges J, Cardoso A, Viaroli P, Newton A, De Wit R, Ibañez C, Reizopoulou S, Somma F, Razinkovas A, Basset A, Holmer M and Murray N 2008 *Eutrophication in Transitional Waters: An Overview* (*Transitional Waters Monographs* vol 2 (1)) (Salento: University Publishinh home) URL `https://publications.jrc.ec.europa.eu/repository/handle/JRC44890`

[13] Mykolaiv State Regional Administration 2017 Regional report on the state of the environment in the Mykolaiv region in 2017 Preprint Mykolaiv State Regional Administration. Department of ecology and natural resources Mykolaiv

[14] Grigoriev B F, Gilman E V and Gilman V A 2005 *Hydrobiological study of the mouth areas of the southern rivers of Ukraine* (Kyiv: Naukova dumka)

[15] Kociolek J P, Theriot E C, Williams D M, Julius M, Stoermer E F and Kingston J C 2014 *Freshwater Algae of North America. Ecology and classification* 2nd ed Aquatic Ecology (Academic Press)

[16] Harwood D M and Nikolaev V A 1995 *Short Courses in Paleontology* **8** 81–106 URL `https://doi.org/10.1017/S2475263000001434`

[17] Bilous O P, Genkal S I, Zimmermann J, Kusber W H and Jahn R 2021 *PhytoKeys* **178** 31–69 ISSN 1314-2011 URL `https://doi.org/10.3897/phytokeys.178.64426`

[18] van der Maarel E 1990 *Journal of Vegetation Science* **1**(1) 135–138 URL `http://doi.org/10.2307/3236065`

[19] Attrill M and Rundle S 2002 *Estuarine, Coastal and Shelf Science* **55**(6) 929–936 ISSN 0272-7714 URL `https://doi.org/10.1006/ecss.2002.1036`

[20] Kirilenko N A and Gerasimiuk B P 2015 *Scientific notes of Ternopil National Pedagogical University. Ser. Biology* (64) 287–290

[21] Adobovskiy V V and Alexandrov B 2006 *Northwestern part of the Black Sea: biology and ecology* (Kyiv: Naukova Dumka)

[22] Petruk V G, Kvaternyuk S M and Gaidey Y A 2015 *Ecological sciences* (1) 65–70

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Study of the energy parameters of the system "solar panels – solar inverter – electric network"

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Abstract. The article presents the results of research into the process of transferring electrical energy from solar panels through a hybrid solar inverter to a three-phase electrical network. An automatic regulation system is presented, which provides power regulation and operation in the mode of maximum power selection from solar panels. The results of the study of the energy efficiency of the system, the parameters of electromagnetic compatibility and the emission of higher harmonic currents are presented.

1. Introduction

The generation and consumption of electricity in the world is constantly growing. At the same time, the generation of electricity from alternative energy sources, including solar photovoltaic panels (PV), is also growing rapidly [1, 2].

In 2020 total electrical power generation of all solar panels was about 760 GWh, what is approximately 3% of the world's total electricity. At the same time, the total amount of solar energy that the Earth receives from the sun per year is $174{\cdot}10^{14}$ PWh, which indicates significant reserves of the possibility of solar generation [3, 4].

The conversion of sunlight into electric current with the help of the photoelectric effect, which occurs in solar photovoltaic cells. The first solar photovoltaic cell was invented by the American scientist Charles Fritts back in the 1880. The first industrially produced solar cell was developed in 1931 by the German engineer Bruto Lange. However, the efficiency of such a solar element was approximately 1%. Since then, the parameters of solar panels have been constantly improving.

Monocrystalline solar panels, polycrystalline solar panels and thin-film solar cells are widely used today. The most important parameters of solar panels are their efficiency and cost. Polycrystalline solar panels have an efficiency of 15.5-18%, and monocrystalline solar panels have an efficiency of 18.5 to 23.5%. However, monocrystalline solar panels have a higher cost, which is due to the fact that monocrystalline panels use monocrystalline silicon with a very high degree of purification above 99.99% [5, 6].

Today, some experimental samples of solar panels have an efficiency above 47%. In 2013, Sharp created a three-layer 4×4 mm indium-gallium-arsenide photocell with an efficiency of 44.4%. Another way to increase the efficiency of solar panels is the use of additional lenses.

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Thus, a group of specialists from the Institute of Solar Energy Systems of the Fraunhofer Society, the companies Soitec, CEA-Leti and the Berlin Helmholtz Center created solar panels using a Fresnel lens, a photocell with an efficiency of 44.7%.

In 2014, the Fraunhofer Institute for Solar Energy Systems created solar cells in which, thanks to a lens focusing light on a very small photocell, the efficiency is 45%. Therefore, the prices of such solar cells are an order of magnitude higher. A promising direction is the creation of nanoantenna-based photocells that work on the direct rectification of currents induced in the antenna of small sizes (about 200-300 nm) by light (that is, electromagnetic radiation of a frequency of about 500 THz). Nanoantennas do not require expensive raw materials for production and have a potential efficiency of up to 85%. But this technology is not yet ready for serial production [7, 8].

The purpose of the study is to obtain scientific results of the process of transferring electrical energy from solar panels through a hybrid solar inverter to a three-phase electrical network. To achieve the purpose, the following objectives were set:

- to develop a simulation model of a system for generating electricity from solar panels to a general industrial network using a solar inverter;
- investigate transients in the electrical network and solar panel when starting the converter.

2. Results and discussion

One of the most important characteristics of solar panels is its current-voltage characteristic, the shape of which depends on the level of solar radiation and temperature. For an example, consider the volt-ampere characteristics of the Era-370W-24V-Mono solar panel (figure 1).

At the same time, the current-voltage characteristics of the solar panel largely depend on the temperature of the panel, while an increase in temperature reduces the generated power (figure 2). Based on figure 2, it can be seen that when the solar panels are heated, the voltage and current, and therefore the power generated by the solar power, decreases. So, it makes sense to cool the solar panels. Thus, lowering the temperature of a heated solar panel from 75 °C to –25 °C will increases the maximum generated power by approximately 35%.

When the current consumed by the solar panel changes, the voltage of the solar panel changes, and thus the power generated by the solar panel changes. At the same time, the dependence of

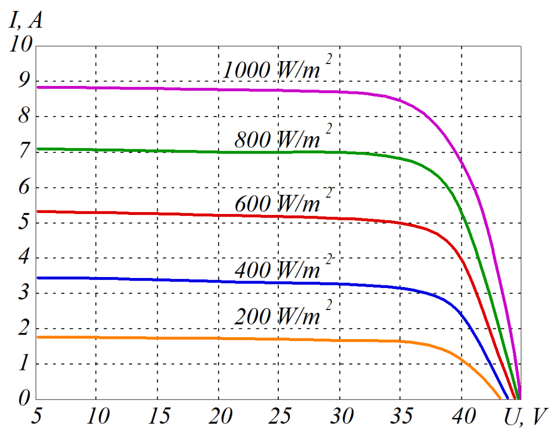

Figure 1. Current-voltage characteristics of solar panel Era-370W-24V-Mono at different levels of solar radiation (with ambient temperature of 25 °C).

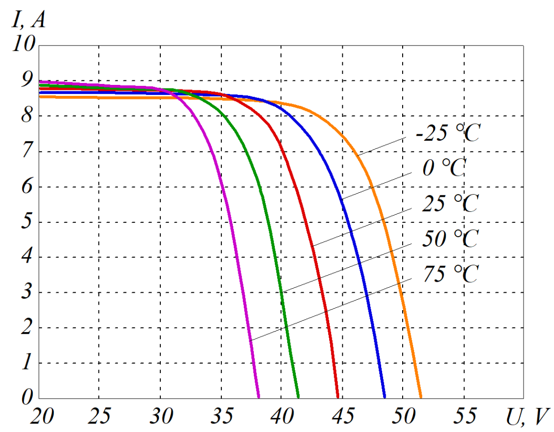

Figure 2. Current-voltage characteristics of solar panel Era-370W-24V at different temperatures (at a sun radiation intensity of 1000 W/m^2).

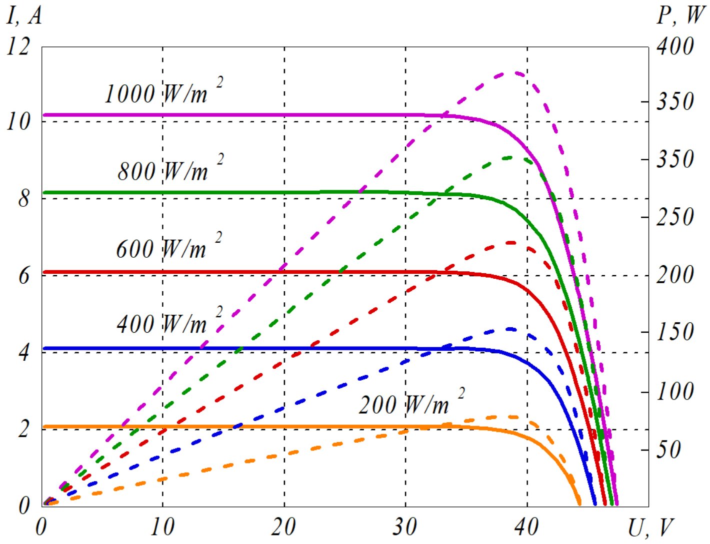

Figure 3. Dependence of the maximum power of the solar panel as a function of the consumed current and the level of solar radiation.

the power of the solar panel on the consumed current is shown in (figure 3). It can be seen that the solar panel has a point of generation of maximum power, which is determined by a certain amount of current consumed by the solar panel. Thus, by adjusting the amount of current consumed by the solar panel, it is possible to enter the maximum power generation mode. This algorithm is called MPPT – maximum power point tracking [9, 10]. Most traditional MPPT algorithms are based on the concept of tilt tracking. One of the typical tilt tracking methods is the algorithm Perturb and Observe (P&O). The disadvantage of this method is the loss of generated power during the search for the point of maximum power generation, which can last for a considerable time.

Determining the maximum power generation point can also be done by exact calculation by polynomial approximation of the solar panel current-voltage characteristics and using solar radiation and temperature sensors [11, 12].

Polynomial approximation of the current-voltage characteristics of the Era-370W-24V-Mono

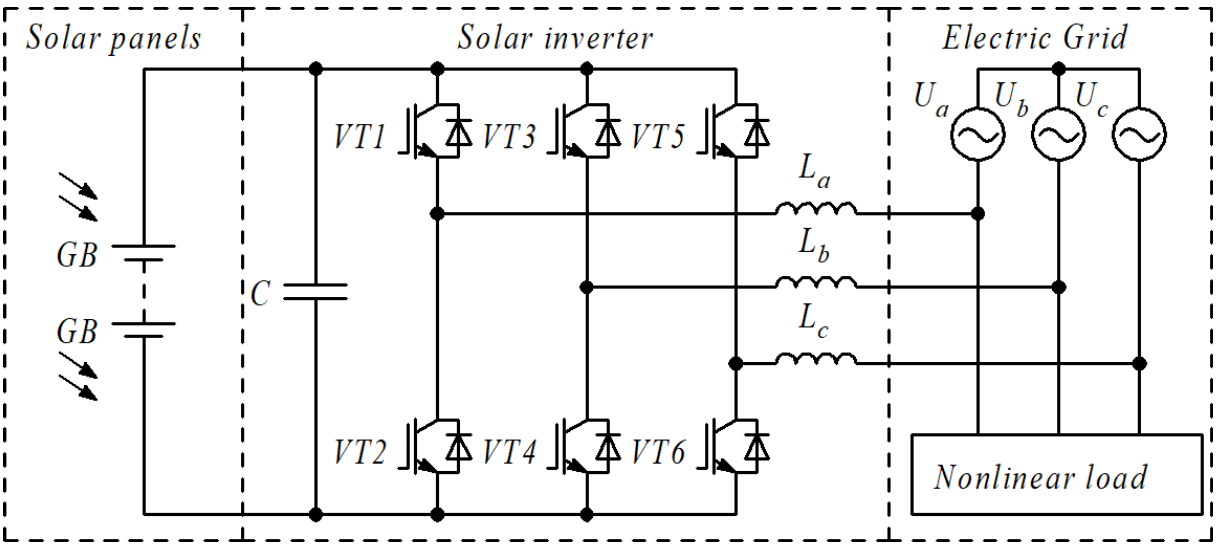

Figure 4. Power generation system “solar panels – solar inverter – electric grid”.

sleeper panel at different levels of sony radiation:

- at a sun radiation intensity of 1000 W/m^2:

$$i_{pv_{1000}}(u) = -44500u^5 + 31375u^4 - 7716u^3 + 764.46u^2 - 24.9u + 18.2; \quad (1)$$

- at a sun radiation intensity of 800 W/m^2:

$$i_{pv_{800}}(u) = -46402u^5 + 33583u^4 - 8494u^3 + 866.8u^2 - 29.1u + 14.7; \quad (2)$$

- at a sun radiation intensity of 600 W/m^2:

$$i_{pv_{600}}(u) = -1980888u^6 + 176912u^5 - 60166u^4 + 9587u^3 - 698.9u^2 + 18u + 11; \quad (3)$$

- at a sun radiation intensity of 400 W/m^2:

$$i_{pv_{400}}(u) = -209032u^6 + 189327u^5 - 64729u^4 + 10272u^3 - 739.4u^2 + 18.68u + 7.097. \quad (4)$$

The obtained polynomials make it possible to analytically determine the generation point of the maximum power of the solar panel as a function of the current consumed by the hybrid inverter. Thus, by regulation the the solar panel current, it is possible to obtain the maximum power that is functionally realized by the semiconductor converter that takes power from the solar panel.

Converters, called solar inverters or hybrid inverters, perform the functions of selecting electrical energy from solar panels, operating in the maximum power generation mode, and ensuring the transmission of electrical energy to the general industrial electrical network (figure 4) [13, 14].

The standards EN 50549-1, EN 50549-2 define the requirements for generating plants to be connected in parallel with distribution networks [15, 16].

A solar inverter, when generation electrical energy to the electrical network, can work both in the voltage-source mode and in the current-source mode. When operating in current-source mode, the solar inverter must operate in a mode similar to the operation of a power active filter with forced formation of a given shape and phase of the current. At the same time, the generation mode in the current source mode has significant advantages, namely: the possibility of operation in the power factor mode close to unity; peration in reactive power compensation mode; operation in the mode of compensation of higher current harmonics caused by non-linear and impulse load of the electrical network. At the same time, the low level of higher harmonics of currents in the electric network causes a decrease in additional power losses in it.

At the same time, for operation in the power active filter mode, a necessary condition for stable operation is the need to maintain the voltage on the solar panels higher than the amplitude value of the linear voltage of the electrical network [17, 18].

To maintain this condition, it is necessary to connect a fairly significant number of solar panels to a solar inverter. When the voltage generated by the solar panels is lower than the amplitude value of the line voltage of the network, then it is necessary to use additional step-up DC–DC converters between the solar panels and the solar inverter [19, 20]. Also, DC–DC converters can be used, providing galvanic isolation between the input and output of the converter. These converters: flyback converter; forward converter; half-bridge push-pull converter junction; full bridge DC–DC converter.

In addition to the function of increasing the voltage from solar panels, DC–DC converters also provide the function of extracting electricity from the solar battery to chemical energy storage devices, such as acid, alkaline or lithium-ion batteries, implemented by semiconductor converters. To implement the function of maximum power selection from the solar panel in

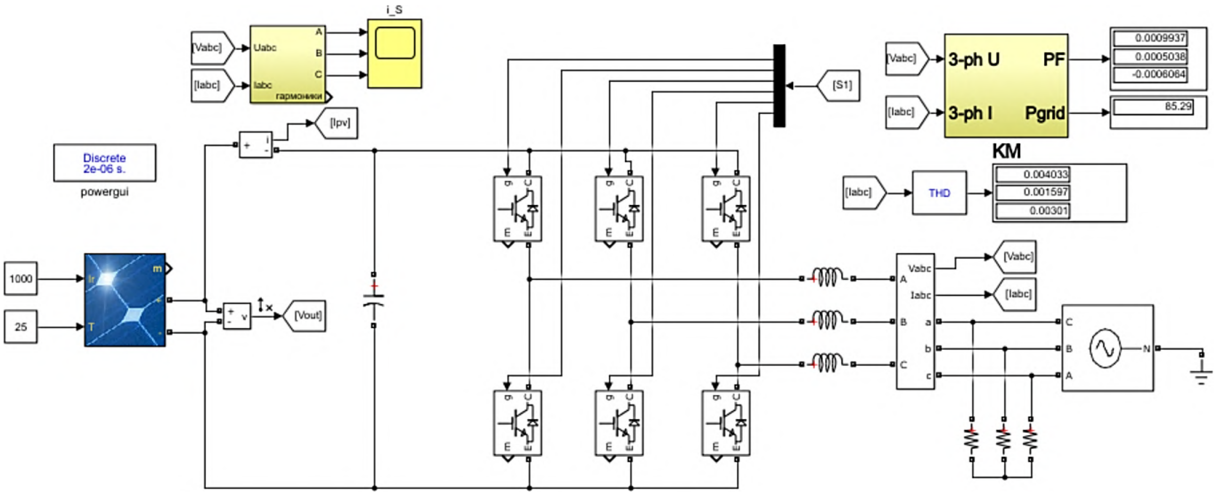

Figure 5. Matlab model of the system “solar panels – solar inverter – electric network”.

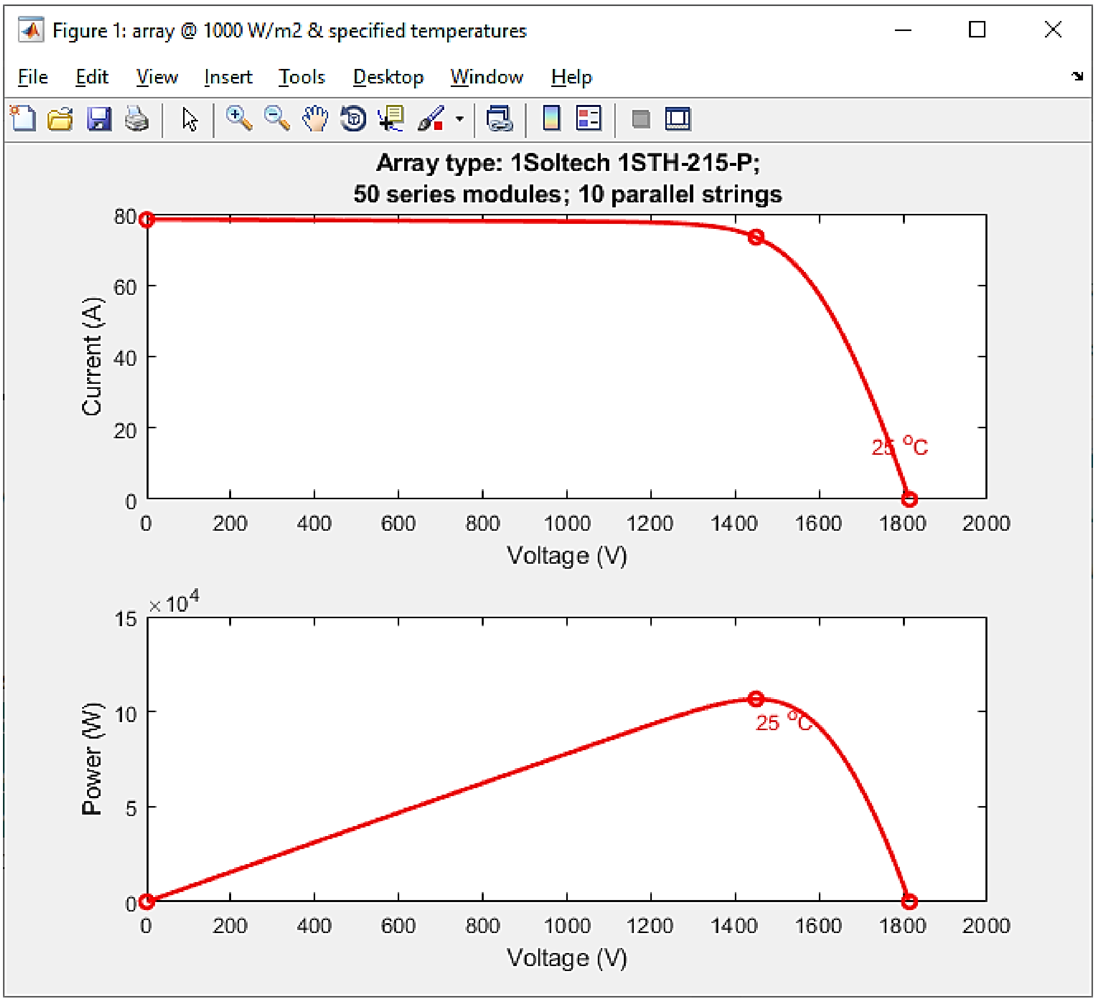

Figure 6. Current-voltage characteristic and power-voltage characteristic.

the DC–DC converter, it is necessary to ensure the implementation of the input current value adjustment for maximum power selection from the solar panel [21, 22].

To determine the parameters of the intensity of the power of electrical energy, which is generated in the sleep panel through the sleep panel, as well as the implementation of the selection of the maximum tension in the sleep panels, a computer simulation model has been developed, which is shown in figure 5.

In the model, the block of solar panels consists of 500 solar panels of the Soltech 1STH-215P type (10 parallel solar panels, 50 serial solar panels in each branch). The maximum current generated by the block of solar panels is 73.5 A. The maximum power generated by the block of solar panels is 1450 V. The maximum power of a block of 500 solar panels is 106.57 kW (at a solar radiation level of 1000 W/m^2 and at a temperature of 25 °C).

The main parameters of the Matlab model of the power active filter are given in table 1.

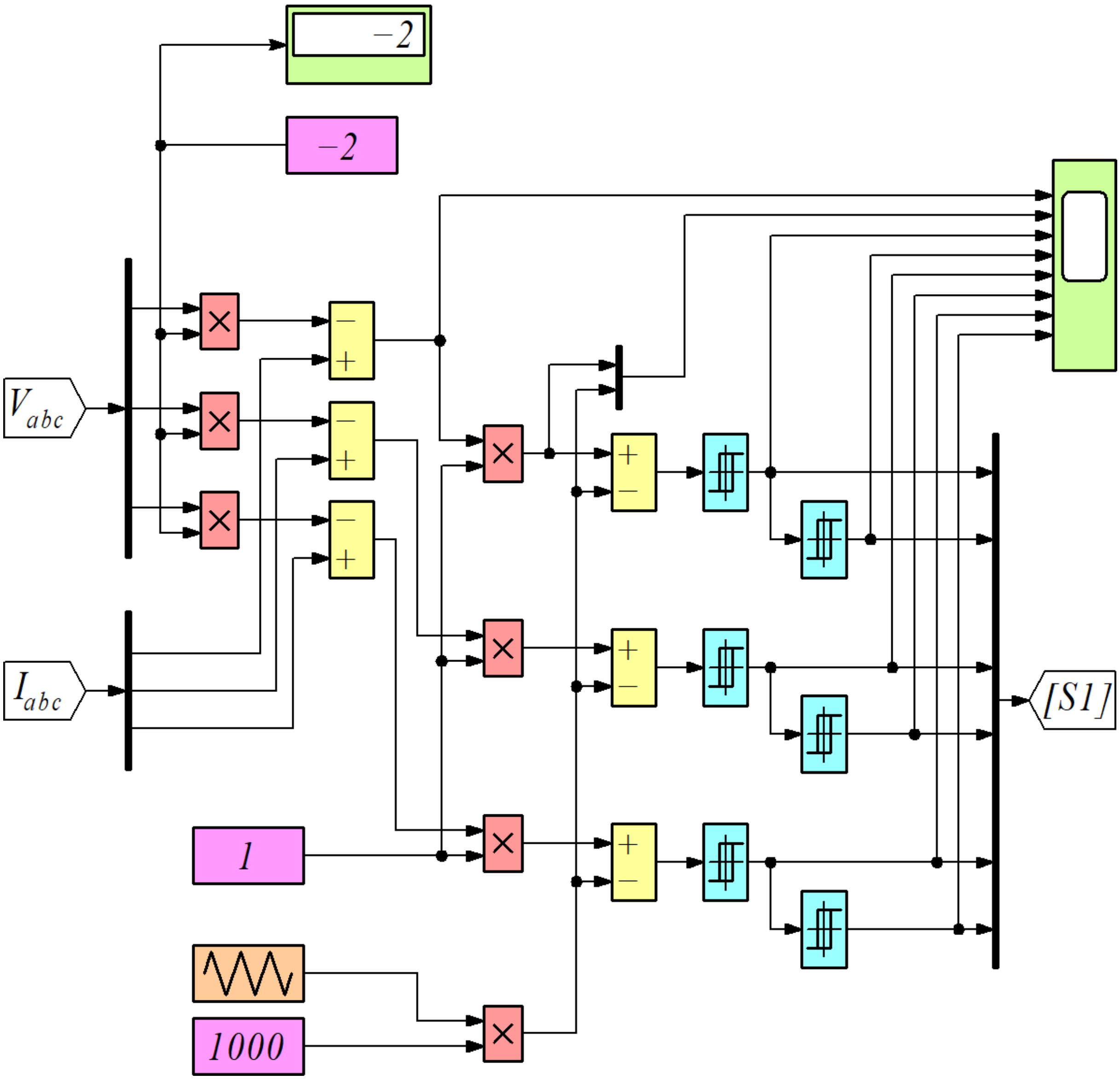

Figure 7. Structure of the hybrid inverter control system.

Table 1. Main parameters of Matlab model.

Parameter	Value
Network voltage, V	220/380
Network load active resistance, Ohm	5
Network inductance, mH	0.1
Inductance of the inductor of the hybrid filter, mH	0.6
Hybrid inverter capacitor capacity, mF	2
PWM frequency, kHz	1-10

Current-voltage characteristic of a set of 500 solar panels simulated in Matlab model is shown in figure 6.

The control system of the hybrid inverter is implemented on the basis of the control system of the power active filter with PWM control with an adjustable modulation frequency from 1 kHz to 10 kHz. The structure of the control system implemented in the model is shown in figure 7.

The implementation of the maximum power selection in the hybrid inverter is implemented by controlling the phase current of the solar inverter by setting the modulation coefficient.

Transient processes of current, voltage and power of solar panels at the start of the solar inverter are shown in figure 8. As can be seen from figure 8, the voltage of the block of solar panels increases from zero during startup.

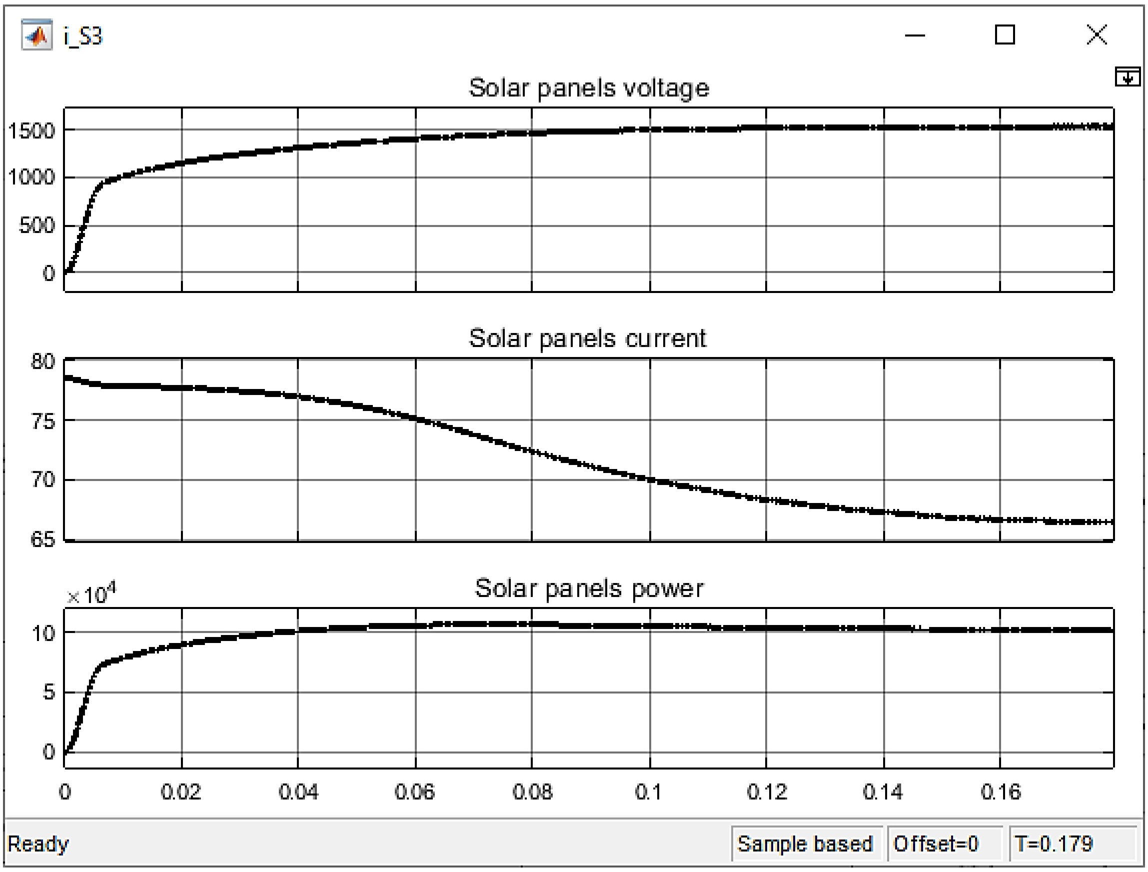

Figure 8. Voltage, current and power of a solar panel delivered by a hybrid inverter.

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As is known, the condition for the implementation of the power factor correction mode and the formation of the sinusoidal form of the generated current is that the voltage in the direct current link of the solar inverter is higher than the amplitude value of the line voltage of the network, into which the energy from the solar panels will be transferred. Therefore, to improve the start-up mode of the solar inverter, it is advisable to perform the start-up with a precharged capacitor of the inverter to the level of a larger amplitude value of the line voltage of the network (figure 9).

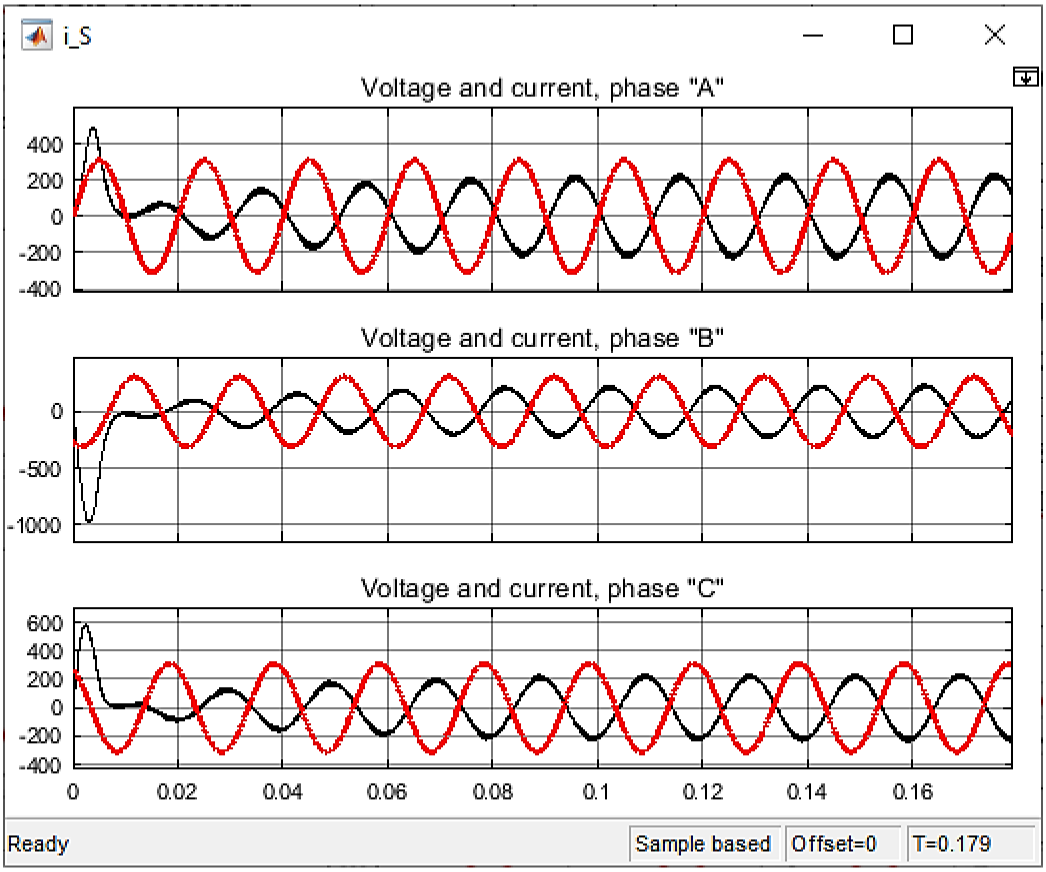

Figure 9. The transition process of transferring electrical energy from the hybrid inverter.

The power factor in the mode of generating electricity to the electric grid is 0.991. The results of the harmonic analysis of the form of the current generated from the solar inverter to the electric grid are shown in figure 10.

As can be seen from figure 10, the current generated from the solar inverter to the electrical network has a harmonic distortion coefficient equal to 3.63%, and the amplitude value of all harmonics in the spectrum does not exceed 2.4%, which meets the requirements of international standards.

To calculate the efficiency of the hybrid inverter, the characteristics of the IGBT module CM1200DC-34S, Mitsubishi with a nominal current of 1200 A and a nominal voltage of 1700 V were taken. The characteristics for which the calculation was given and which determine power losses are shown in figure 11.

The results of polynomial approximation of the energy characteristics of power transistors at a temperature of 25 °C are given in the following expressions.

When using the developed algorithm, power losses were determined, as well as the quality of

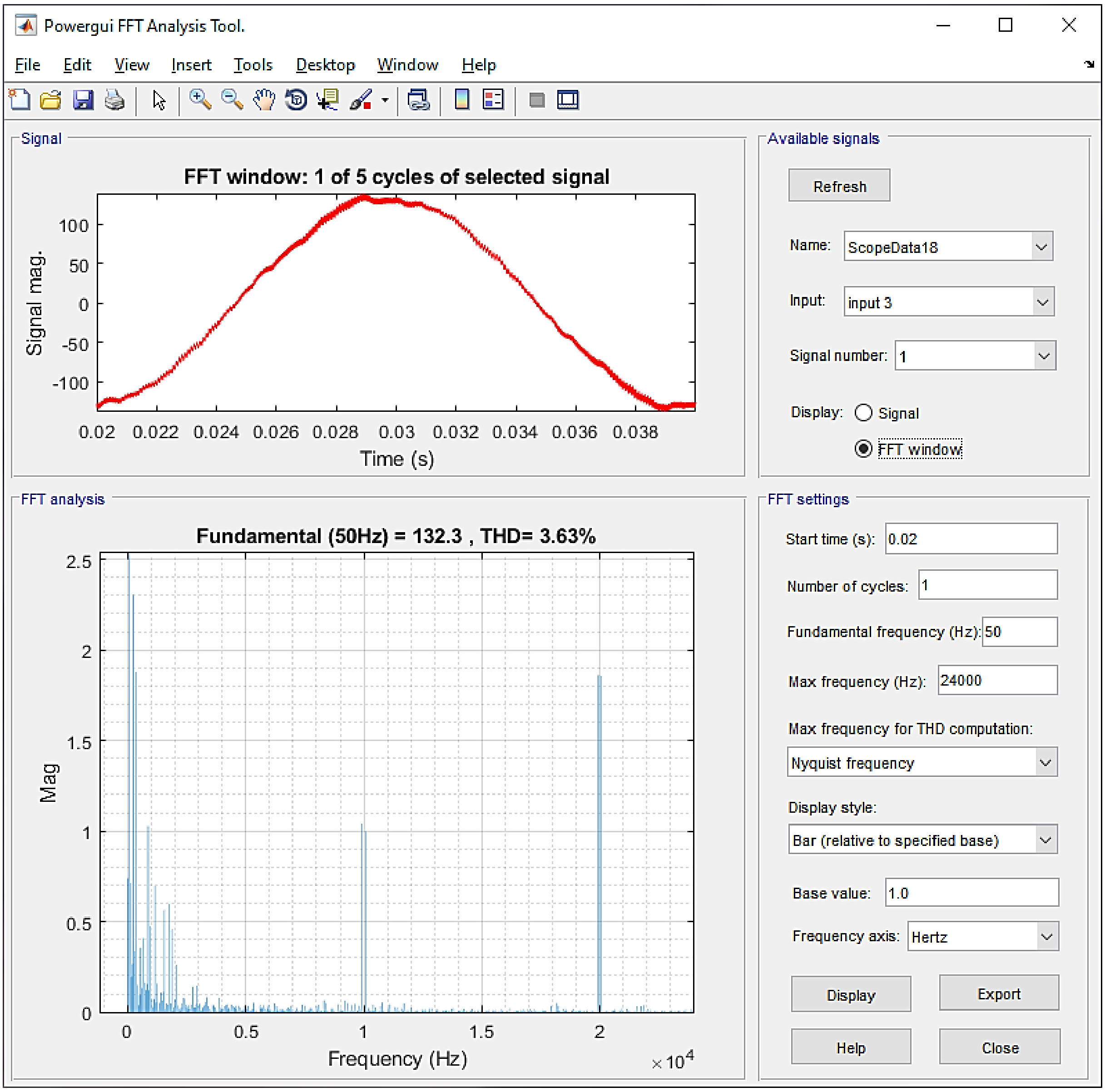

Figure 10. Harmonic analysis of the shape of the current generated from the solar inverter.

the realized current when setting different modulation frequencies.

$$U_{ce}(I_c) = -0.162I^4 + 0.942I^3 - 2.009I^2 + 2.746I + 0.57; \tag{5}$$

$$U_{fw}(I_f) = -0.185I^4 + 1.054I^3 - 2.171I^2 + 2.735I + 0.68; \tag{6}$$

$$E_{on}(I_c) = 0.2406I^2 - 0.006I + 0.0496; \tag{7}$$

$$E_{off}(I_c) = 0.0587I^2 + 0.1842I + 0.0547; \tag{8}$$

$$E_{rec}(I_f) = 0.0054I^5 - 0.0368I^4 + 0.1002I^3 - 0.1601I^2 + 0.2309I + 0.0227. \tag{9}$$

The calculation carried out during modeling determined the dependence of the amount of power loss in one power switch of the inverter as a function of the PWM frequency in figure 12.

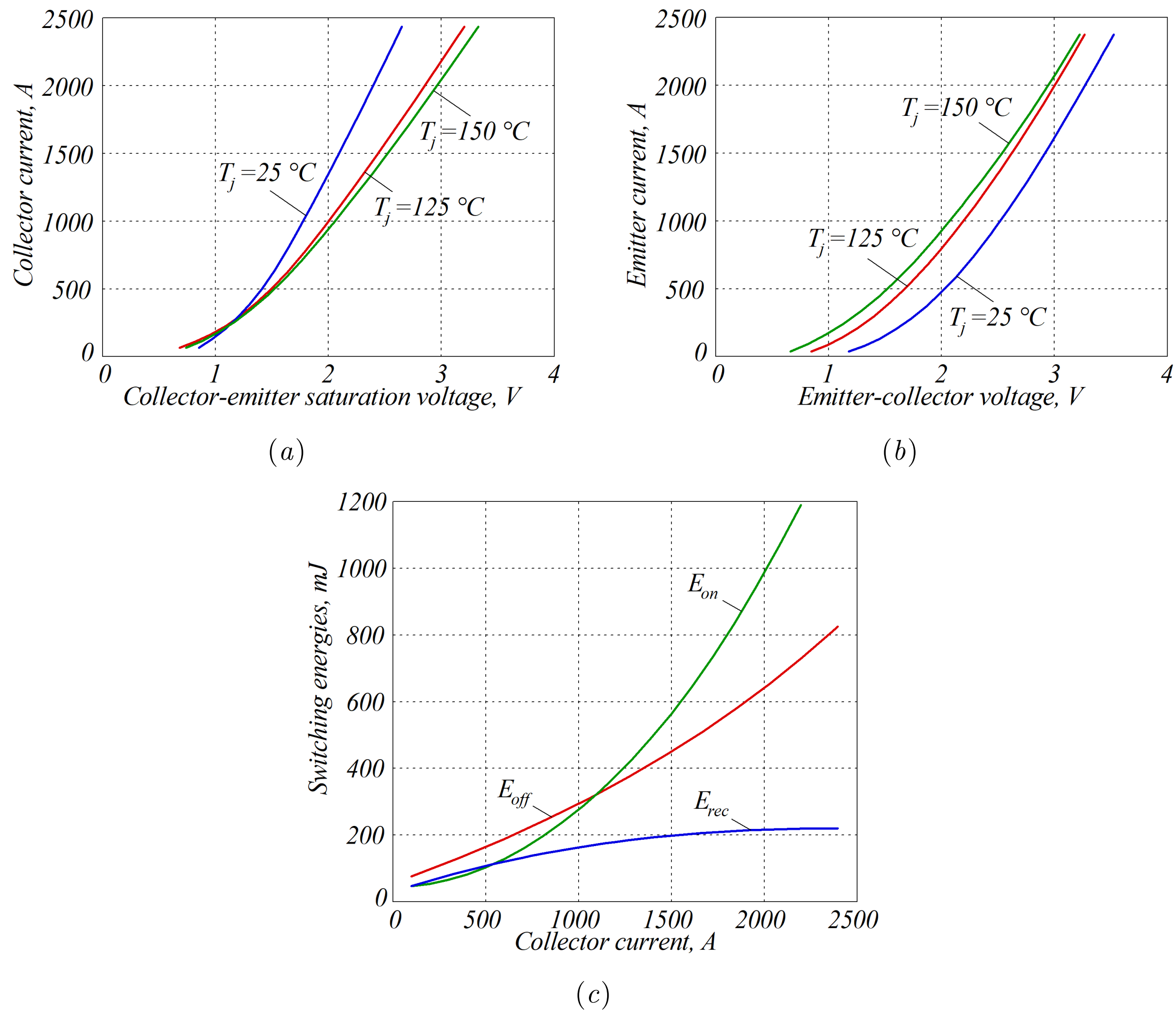

Figure 11. Energy characteristics of the CM1200DC-34S module: (a) volt-ampere characteristic of the transistor; (b) volt-ampere characteristic of the reverse diode; (c) dependences of the switch-on energy, switch-off energy and reverse diode recovery energy from the commutated current.

Dependence of power losses in the CM1200DC-34S power transistor on the PWM frequency at a DC link voltage of 1500 V and a current amplitude of 223 A (maximum power point of solar panels).

Thus, the efficiency of the hybrid inverter when transferring electricity from the solar panels to the electrical network was from 98.4% at a PWM frequency of 1 kHz to 92.7% at a PWM frequency of 6 kHz.

3. Conclusions

The article shows that the generated power from solar panels has a maximum point, which depends on the amount of current consumed from the solar panel. The circuit solutions of semiconductor converters are determined, which provide the maximum power extraction modes from solar panels and the transmission of electricity to general industrial electrical networks with high quality parameters.

The developed computer simulation model of a system for generating electricity from solar

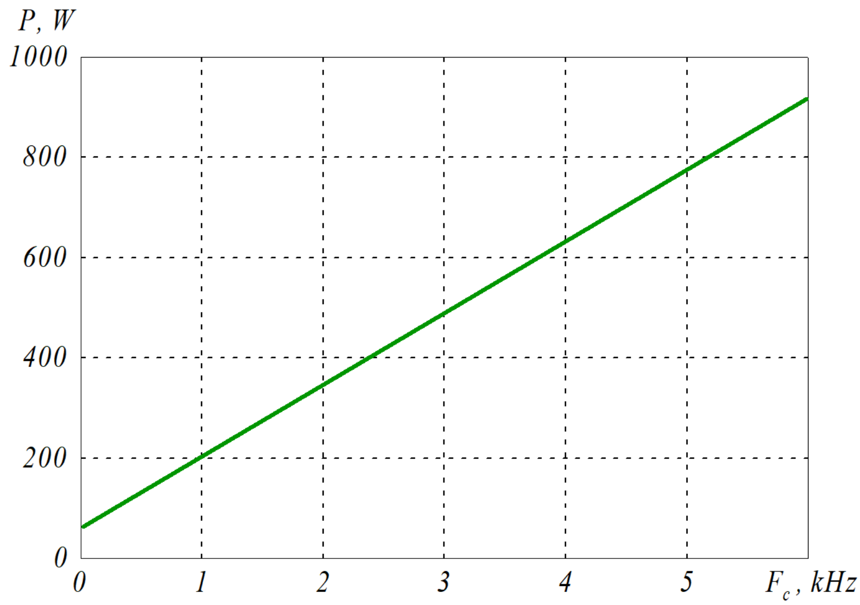

Figure 12. Dependence of power losses in the CM1200DC-34S power transistor.

panels of Soltech 1STH-215P types to a general industrial network using a solar inverter with a PWM control system, which makes it possible to transfer electrical energy with a power factor close to unity (0.98) with a low level of higher harmonics (total harmonic distortion 3.36%).

The model also explores the transients in the electrical network and the solar panel when starting the converter. Recommendations are given for starting a solar inverter with a pre-charged capacitor, which will improve the quality of the current in the start mode.

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References
[1] Anaba S A and Olubusoye O E 2020 Electricity generation from renewable resources *Affordable and Clean Energy* ed Leal Filho W, Azul A M, Brandli L, Lange Salvia A and Wall T (Cham: Springer International Publishing) pp 1–13 ISBN 978-3-319-71057-0 URL https://doi.org/10.1007/978-3-319-71057-0_137-1
[2] Ghandriz Y, Ziaiean Noorbakhsh S M, Gavagsaz-Ghoachani R and Phattanasak M 2021 Effect of wide observation of nature in renewable energy engineering education *2021 Research, Invention, and Innovation Congress: Innovation Electricals and Electronics (RI2C)* pp 193–198 URL https://doi.org/10.1109/RI2C51727.2021.9559741
[3] Geisz J F, France R M, Schulte K L, Steiner M A, Norman A G, Guthrey H L, Young M R, Song T and Moriarty T 2020 *Nature Energy* **5**(4) 326–335 ISSN 2058-7546 URL https://doi.org/10.1038/s41560-020-0598-5

[4] Gosavi S S, Mane H G, Pendhari A S, Magdum A P, Deshpande S, Baraskar A, Jadhav M and Husainy A 2021 *Journal of Thermal Energy Systems* **6**(1) 16–24 URL https://www.researchgate.net/publication/349529329
[5] Sugianto 2020 *INTEK: Jurnal Penelitian* **7**(2) 92–100 URL https://doi.org/10.31963/intek.v7i2.2625
[6] Wei N T J, Nan W J and Guiping C 2017 *IOP Conference Series: Materials Science and Engineering* **217** 012011 URL https://doi.org/10.1088/1757-899X/217/1/012011
[7] Pinheiro Caetano I M, N Torres J P and Marques Lameirinhas R A 2021 *Nanomaterials* **11**(11) 2911 ISSN 2079-4991 URL https://doi.org/10.3390/nano11112911
[8] Rabienejhad M J, Davoudi-Darareh M and Mazaheri A 2021 *Chinese Physics B* **30**(9) 098503 URL https://doi.org/10.1088/1674-1056/abea8e
[9] Chitransh A and Kumar S 2021 *Indian Journal of Engineering and Materials Sciences* **1**(2) 1–4 URL https://doi.org/10.35940/ijee.A1809.111221
[10] Ryu D, Kim Y J and Kim H 2018 Optimum MPPT Control Period for Actual Insolation Condition *2018 IEEE International Telecommunications Energy Conference (INTELEC)* pp 1–4 URL https://doi.org/10.1109/intlec.2018.8612419
[11] Louzazni M and Al-Dahidi S 2021 *Renewable Energy* **174** 715–732 ISSN 0960-1481 URL https://doi.org/10.1016/j.renene.2021.04.103
[12] Nerubatskyi V, Plakhtii O and Hordiienko D 2022 Efficiency Analysis of DC-DC Converter with Pulse-Width and Pulse-Frequency Modulation *2022 IEEE 41st International Conference on Electronics and Nanotechnology (ELNANO)* p 571–575 URL https://doi.org/10.1109/ELNANO54667.2022.9926762
[13] Choi W, Jung K and Sarlioglu B 2020 Power Control of Hybrid Grid-Connected Inverter to Improve Power Quality *2020 IEEE Energy Conversion Congress and Exposition (ECCE)* p 3741–3745 URL https://doi.org/10.1109/ECCE44975.2020.9235627
[14] Imdadullah, Alamri B, Hossain M A and Asghar M S J 2021 *Electronics* **10**(17) 2179 ISSN 2079-9292 URL https://doi.org/10.3390/electronics10172179
[15] 2019 CSN EN 50549-1. Requirements for generating plants to be connected in parallel with distribution networks - Part 1: Connection to a LV distribution network - Generating plants up to and including Type B
[16] 2019 CSN EN 50549-2. Requirements for generating plants to be connected in parallel with distribution networks - Part 2: Connection to a MV distribution network - Generating plants up to and including Type B
[17] Nerubatskyi V, Plakhtii O and Hordiienko D 2021 Control and Accounting of Parameters of Electricity Consumption in Distribution Networks *2021 XXXI International Scientific Symposium Metrology and Metrology Assurance (MMA)* pp 1–4 URL https://doi.org/10.1109/MMA52675.2021.9610907
[18] Soedibyo, Syahputra R, Ashari M, Budi A L S, Anam S and Soeprijanto A 2020 Photovoltaic Voltage and Power Cell Characteristics Based on Air Quality Index and Pollution Percentage Level *2020 1st International Conference on Information Technology, Advanced Mechanical and Electrical Engineering (ICITAMEE)* pp 117–121 URL https://doi.org/10.1109/ICITAMEE50454.2020.9398467
[19] Devie S R, Alagammal S and Prabha N R 2017 Efficient single switch isolated high step up DC-DC converter with constant output voltage for solar energy sources *2017 IEEE International Conference on Intelligent Techniques in Control, Optimization and Signal Processing (INCOS)* pp 1–6 URL https://doi.org/10.1109/ITCOSP.2017.8303150
[20] Kaci L, Arab D A H, Zirmi R, Semaoui S and Boulahchiche S 2021 Solar inverter performance prediction *2020 6th International Symposium on New and Renewable Energy (SIENR)* pp 1–5 URL https://doi.org/10.1109/SIENR50924.2021.9631900
[21] Lahooti Eshkevari A, Mosallanejad A and Sepasian M S 2021 *IET Power Electronics* **14**(1) 225–238 URL https://doi.org/10.1049/pel2.12027
[22] Sakib S and Siddique M A B 2019 Modeling and Simulation of Solar Photovoltaic Cell for the Generation of Electricity in UAE *2019 5th International Conference on Advances in Electrical Engineering (ICAEE)* p 66–71 URL https://doi.org/10.1109/ICAEE48663.2019.8975490

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The usage of probiotic microorganisms in production technology of European grayling fish stock

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The usage of probiotic microorganisms in production technology of European grayling fish stock

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Abstract. European grayling is a perspective object of a recreational fishing. In addition, the presence of this species in sufficient quantities in rivers has a positive influence on the formation of the recreational attractiveness of mountain regions, where tourism is one of the main sources of local communities existence. However, grayling stocks in the watercourses of Ukraine are significantly depleted nowadays, and populations are in a condition of lack, what has led to the inclusion of this species into the Red Book of Ukraine. Working out of biotechnologies of artificial reproduction of rare fish species in aquaculture conditions for the further reintroduction of the resulting offspring into natural water bodies takes an important place in the system of environmental protection measures to preserve biodiversity. After all, the reintroduction into nature of artificially obtained fish fry is one of the effective ways to restore the optimal number and structure of rare fish species natural populations, and this, in turn, will allow in the future to restore the limited exploitation of the stock of these fish species. One of the critical artificial fish reproduction technology links is the transfer of larvae to external nutrition. Namely on this stage the highest mortality rates are observed. The usage of live feeds as a starter fodder can significantly improve the situation. Forage organisms, in addition to having high nutritional value, can serve as delivering tools of various targeted products, including probiotics, to a fish larvae organism. The assessment of the usage of probiotic strain *Lactobacillus casei* IMV B-7280 feasibility is carried, and also the possibility of usage the culture *Daphnia magna* Straus, 1820 grown in the presence of trehalose lipids, within the technology of early feeding of the European grayling *Thymallus thymallus* (Linnaeus, 1758). It was shown that the larvae of the European grayling, which received investigated probiotic microorganisms strain, had 15% bigger weight on the final stages of feeding than the larvae of the control group. Introduction to the diet of grown-up grayling larvae of the culture *Daphnia magna*, previously received of common cultivation with microalgae *Desmodesmus armatus* (Chodat) E.H.Hegewald 2000 with addition of trehalose lipids, contributed to the reduction of larval mortality and the acceleration of their growth rate. Further improvement of proposed approaches of growing grayling fish planting material can be extrapolated to other fish species and in the future may be applicable in the process of growing rare fish species in conditions of farm aquaculture fish farms, what will allow them to be involved into environmental protection activities by placing appropriate orders. This, in its turn, will contribute to the stable development of communities in rural areas.

1. Introduction

The development of methods and practical measures for gene pool preservation and population size restoration of rare and vulnerable aboriginal fish species requires the implementation of integrated research, among which the work out of reproduction biotechnologies of such species in the conditions of aquaculture, takes prominent place. European grayling, in addition to having high food and taste qualities, is a promising object of recreational fishing. Due to this fact, the presence of this species in sufficient quantity in rivers has a positive influence on the formation of recreational attractiveness of mountain regions, where one of the main sources of existence of local communities is tourism. However, nowadays grayling stocks in the watercourses of Ukraine are currently significantly depleted, and populations are in a condition of lack, what has led to the inclusion of this species into the Red Book of Ukraine. Restoring the optimal number and structure of natural populations is one of the main prerequisites for removing the species from the protection lists, including from the Red Book of Ukraine, and will allow limited exploitation of fish stocks in the future.

Usage of aquacultural methods of supporting the quantity of rare and endangered fish has found an application in the countries of the European Union. Thus, due to the artificial fish reproduction and the growing of resulting offspring to a viable condition for further stocking in the Baltic countries, it became possible not only to restore the normal population size of brown trout, and also to implement licensed fishing for amateur fishermen. There is the same situation with the population of Danube salmon in Slovakia.

The development of correction technologies of live feeds nutrient composition in order to improve their nutritional value will allow to increase the young fish survival on early stages of development and thereby to reduce the cost of receiving fish planting material works. Improved and developed technologies and approaches of receiving and growing rare fish species planting material to a viable condition, including the European grayling, in future will find an application in the process of growing these species in conditions of aquaculture fish farms, what will allow in the future find application in the process of growing these species in the conditions of farm aquaculture fish farms, which will allow them to be involved into environmental protection activities by placing appropriate orders. This, in its turn, will contribute to the stable development of communities in rural areas.

Usage of probiotics in aquaculture as treatment-and-prophylactic means of dysbiosis correction is an efficient method of compensation of negative effect of strenuous conditions of fish keeping within industrial aquaculture. In addition to increasing various fish diseases resistance, probiotics are able to synthesize a number of extracellular enzymes, what increases the bioavailability of forages and ensures decreasing in its costs, what contributes to the intensification of fish growing processes [1]. Usage of probiotics also positively influences on stabilization of digestive tract functions and improving its enzymatic activities, normalizing of mucus formation on the fish body surface and improving of the gill apparatus [2]. Probiotic microorganisms contribute to enhancing of phagocytic, lysozyme, complement acrivities, and also expression of various cytokines in fishes [3].

Among the great variety of probiotic microorganisms, representatives of the genus *Lactobacillus* cause a substantial interest for aquaculture. It is based on the fact that there were not found any species of *Lactobacillus*, which could be pathogenic or conditionally pathogenic to aquatic organisms [4]. Due to a number of adaptive capabilities, namely a high level of adhesion, synthesis of organic acids and hydrogen peroxide, resistance to adverse conditions of digestive tract, they are able to colonize digestive tract of hydrobionts successfully and resist pathogenic microflora [5].

One of the main technological problems of the use of probiotic preparations is related to ensuring targeted delivery of the appropriate bacteria to fish organism. Probiotics introduction directly into water leads to its dispersion in a significant volume of the environment, its introduction into granular forages is also problematic - in the process of extrusion, which is used in the production process of most types of modern production forages, the viability of microorganisms can significantly decrease. Live feed can serve as a reliable vector for targeted delivery of probiotics into fish organism [6]. Traditionally in aquaculture brine shrimp nauplia are used as a live feed, which are of the right sizes for feeding early larvae of the vast majority of fish species [7]. On the later stages of fish development, it is more expedient to use larger feed organisms, in particular various species of Cladoceran [8]. It makes improving the increasing technologies for a biomass of live feeds an urgent issue, namely searching for inexpensive alternative environments, a possibility of nutrient correction, and most important – the acceleration of cultivation rates. The usage of biosurfactants allows to improve absorption of nutrient substrates by forage organisms, in particular by daphnias, what ensures the growth rate of their biomass acceleration. Within the biotechnology of receiving biosurfactants the main method is a microbial synthesis. In particular, in such way trehalose lipids can be received. At the same time, it is important to understand whether the appropriate preparations will not have a negative impact on fish, which is fed with live feeds grown with the usage of biosurfactants.

The usage of live feeds and probiotics helps to increase the viability of young fish. This is especially relevant in production of fish planting material intended for introduction into nature. After all, the living conditions change during fish transfer from comfortable aquaculture conditions to natural water reservoirs is often the cause of large losses. Receiving of fry with high viability is especially relevant within carrying out work on a rare fish species reproduction.

Taking into account the above, the aim of the work was to assess the feasibility of probiotic strain *Lactobacillus casei* IMV B-7280 usage and also, the opportunity of usage the culture Daphnia magna grown in the presence of trehalose lipids, within the technology of early feeding of the European grayling *Thymallus thymallus* (Linnaeus, 1758).

2. Materials and methods

Experimental growing of European grayling larvae took place in 2021 on the State Enterprise "Trout hatchery "Lopushno" basis, which belongs to the department of the State agency of land reclamation and fisheries of Ukraine. Incubation of caviar and growing of fish planting material was carried out according to generally accepted recommendations for grayling [9]. Larvae were reared in 20×40 cm trays with a water volume of 18 liters. During all the time of experimental growing the quality of water was controlled with Combo Water Testing Meter AZ-86031.

In both control and experimental groups, the initial number of larvae in trays was 500 individuals. Experimental feeding of larvae was started on the ninth day after hatching from eggs. Introduction of forage was carried out every hour from 8:00 a.m. to 7:00 p.m., alternating with starter dry forage Biomar and live feeds. As starter live feeds nauplia artemia was used, namely *Artemia* spp.

On the first stage of experiment with a duration of 13 days grayling larvae received corresponding dry forage Biomar and intact nauplia artemia, and larvae of experimental group – dry forage and nauplia artemia enriched by probiotic microorganisms culture *Lactobacillus casei* IMV B-7280.

The cultivation of artemia was carried out with common aquacultural method [10] . After the procedure of cleaning cyst sash and cysts which did not hatch, nauplia artemia were transferred to a fresh environment with the appropriate salinity, where lyophilized cultures of probiotic microorganisms with a concentration of 5×10^{11} CFU/l were introduced. The bioencapsulation procedure lasted for 12 hours with constant aeration and lighting.

On the second stage of experiment with a duration of 7 days was investigated the expediency of live feeds usage within the technology of feeding grown grayling larvae. From individuals, which previously got the standard ration without probiotics, the control group of grayling larvae was created and they were fed with the dry forage Biomar, and also research group in which fish got live feeds besides the dry forage, namely *Daphnia magna* Straus, 1820. Feeding was carried out every hour and half during daylight hours. The initial number of grayling larvae is 200 individuals in each tray. In order to increase the nutritional value of forage organisms, daphnia was cultivated together with the green microalgae *Desmodesmus armatus* (Chodat) E.H.Hegewald 2000 [11]. Acceleration of the growth rate of biomass was provided by the addition of trehalose lipids preparation, which was received from the culture fluid of *Rhodococcus erythropolis*.

All researches were performed in triplicate. Effects of dietary treatment were analyzed by a one-way analysis of variance (ANOVA), followed by Tukey's or Student's post hoc test to determine significant differences. Previous to statistical analysis, data were transformed with natural logarithm if identified as non-homogenous (Levene's test) to meet the assumptions for statistical methods. Mean values were considered significantly different at $p \leq 0.05$. Statistical analysis was computed using MS Excel software and STATISTICA 6.0 application package.

3. Ethical considerations

The research conducted in this study adhered to a comprehensive set of ethical principles and guidelines in compliance with both national regulations in Ukraine and institutional policies. Below are the specific ethical considerations and procedures that were followed throughout the experiment:

3.1. National and institutional compliance

1. All aspects of this research were conducted in strict accordance with the principles outlined in the European Convention on the Protection of Vertebrate Animals Used for Research and Other Scientific Purposes. This convention outlines the ethical treatment of animals in scientific research and serves as a fundamental guideline for our ethical approach.
2. We also adhered to the relevant national legislation, specifically the Law of Ukraine "On the Protection of Animals from Cruelty". This law governs the ethical treatment and welfare of animals used in research within the jurisdiction of Ukraine.

3.2. Animal welfare and care

1. Throughout the entire duration of the experiment, we maintained a rigorous standard of constant care for the animals involved. This included regular monitoring of their health and well-being, with immediate action taken to address any signs of distress or discomfort.
2. Special attention was given to ensuring that the animals did not experience any unnecessary pain, suffering, or anxiety. Procedures and handling techniques were designed to minimize stress and discomfort.
3. In cases where it was necessary to euthanize animals, we employed humane methods that were consistent with internationally accepted practices to minimize suffering.
4. To minimize the impact on the animal population, we carefully selected the smallest necessary number of animals required to achieve the research objectives effectively.

3.3. Personnel qualifications

All individuals involved in conducting the experiments and caring for the animals possessed appropriate educational and professional training. This ensured that the highest standards of animal welfare and ethical conduct were upheld throughout the study.

4. Results and discussion

At the the Trout hatchery "Lopushno" the experience of artificial reproduction of aboriginal salmon fish is accumulated, including European grayling what is highlighted in a number of scientific publications [12, 13]. Further researches are aimed at improving proven technologies. Special attention is paid to the problem of young fish mortality reducing and accelerating its growth rates.

On this farm, the incubation of grayling caviar is carried out in horizontal tray apparatuses for salmon fish. Due to the lack of an opportunity to heat the water, the duration of incubation of eggs and hatching periods at the enterprise depend on weather conditions and may significantly differ in different years. An average embryogenesis of grayling lasts 22-24 days [13]. In 2021 the interval between the beginning and the end of embryos hatching from caviar took 11 days. Larvae transition to exogenous nutrition began on the sixth day after hatching, and after 9 days 100% of survived larvae switched to external nutrition, what correspond with the data of other authors [13]. Accordingly, that is why namely on the 9th day after the embryos hatching completion, experimental grayling larvae feeding was started, and was carried out in two stages.

During the experiment, the water temperature in the trays increased by approximately 2 °C, while the concentration of oxygen dissolved in the water, changed insignificantly (figure 1). In general, the quality of water corresponded to the norm [9].

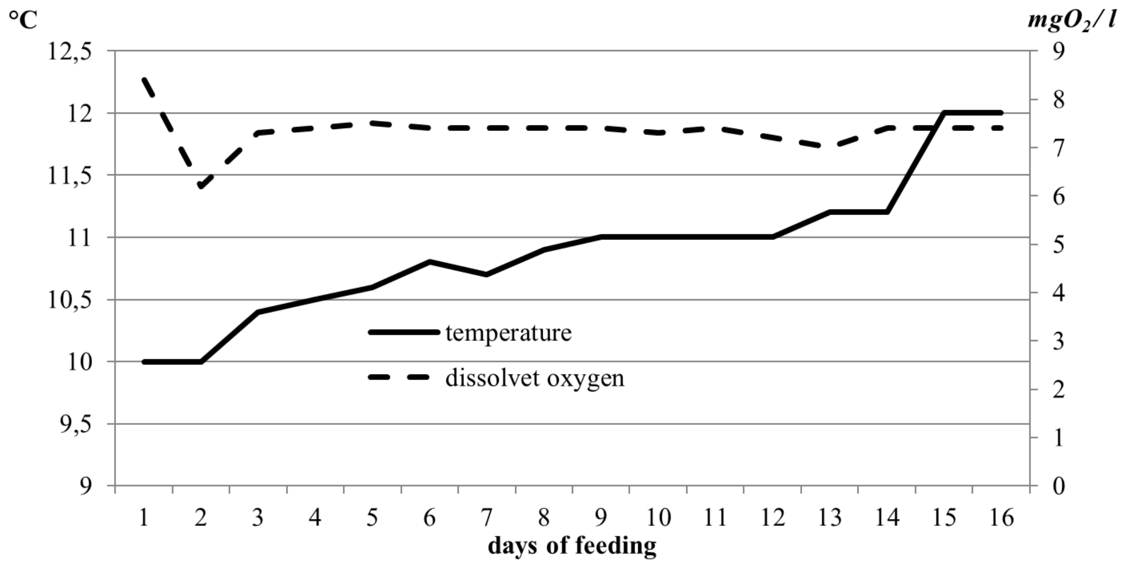

Figure 1. Dynamics of water temperature and concentration of oxygen dissolved in water during experimental European grayling larvae feeding.

Research results showed that grayling larvae, which received encapsulated into artemia lactobacilli, were characterized by a higher growth rate at all stages.

Thus, with the same average initial body weight of 0.02 g, after thirteen days, individuals of the research group were 15% heavier than larvae from the control group (figure 2). It is known that probiotic microorganisms are able to product extracellular digestive enzymes, including protease [2]. As a result, nutrients are engulfed and absorbed more efficiently during a simultaneous use with probiotics, and forages, enriched with them, have a higher nutritional value.

Besides, it is known that *L. casei* has the ability to produce a specific bacteriocin-caseicin, which has an expressive bacteriostatic and weak bactericidal action. Caseicin can be producted extracellularly as well as inside a cell in a ratio of 50 : 1 [14]. It can be assumed that this bacteriocin contributes to the increased elimination of pathogenic and conditionally pathogenic microorganisms in nauplia artemia, which are received from cysts collected of natural conditions. It allows to protect young fish to some extent from pathogens which may be transmitted with

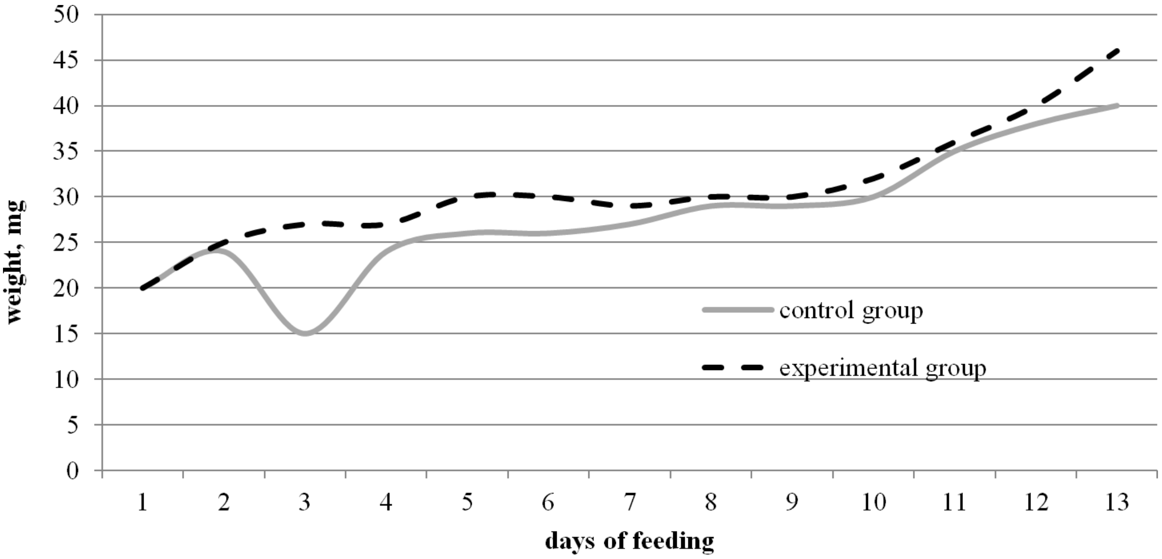

Figure 2. Dynamics of body weight accumulation of European grayling larvae during feeding with artemia, non-encapsulated and encapsulated with lactobacilli.

live feeds.

The positive effect of using live feeds lies in the fact that they have the necessary set of nutrients for fish, as well as contain their own hydrolytic enzymes which improve the functional activity of fish larvae digestive tract, increase the level of feeds conversion and their digestibility. All of this contributes to the growth intensification processes of young fish.

The introduction of *D. magna* to ration of European grayling youth contributed to the faster accumulation of fish body weight. Thus, the average daily gain of individuals of the control group amounted 3.1 g, and the larvae of the research group – 4.3 g, what is 36% more (figure 3).

Producers of a large quantity of essential micronutrients for fish are microalgae [15, 16].

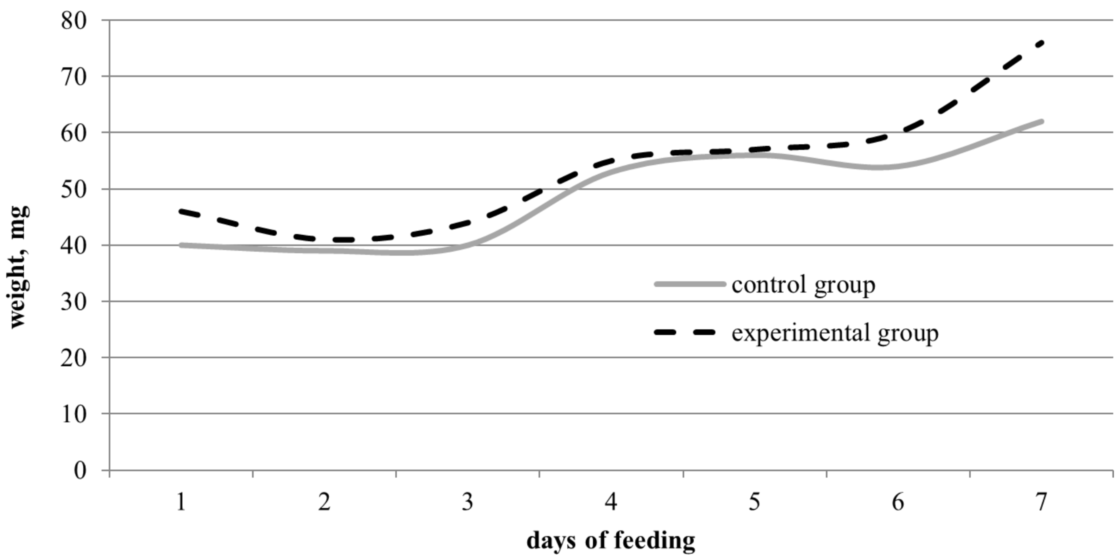

Figure 3. Dynamics of body weight accumulation of growing European grayling larvae under conditions of adding live feed to the diet.

However, due to the existing cell wall, algae are often poorly digested by fish. In return, phytomass is partially digested in a digestive tract of zooplankton, what makes it bioavailable to a fish organism [11]. According to this, combined cultivation of microalgae with feed zooplankton allows to receive live feeds with improved nutritional value.

According to this, one of the problems of receiving a sufficient amount of live feeds for young fish feeding is the rapid increase of its biomass. This can be achieved with the help of biosurfactants usage. Among the wide variety of biological surface-active substances, trehalose lipids are perspective for use – it is the one of glycolipids groups, in which the carbohydrate component is represented by trehalose. Trehalose is a disaccharide in which 2 residues of D-glucose are connected by an α, α-glycosidic bond. Trehalose dissolves well in water and alcohols. According to this, its compounds with fat acids and other lipid nature substances have amphipathic properties, i.e., they dissolve in water and as well as non-polar solvents. It allows nutrients in a digestive tract to form micelles and to transform hydrophobic compounds into a soluble condition [17]. The ability to form micelles, on the one hand, ensures emulsification of fats, what speeds up their digestion, and on the other hand, facilitates the transportation through biological membranes, thereby improving an absorption in intestines.

Previous researches have pointed out that the introduction of biosurfactants speeds up the growth rate of forage zooplankton cultures and also reduces the effective concentration of biocides [18].

Trehalose lipids are synthesized in significant quantities by *Rhodococcus erythropolis* and are accumulated in a culture liquid. The question remains whether the rests of biosurfactants or their derivatives will have a negative effect on young fish. Previous researches have pointed out that the introduction of growing grayling larvae of live feeds biomass, grown by co-cultivation with green algae in presence of trehalose lipids, intensifies the growth rate of fish larvae mass, as well as contributes to increasing of survival rate of fish of the research group in comparison with the control group of individuals (figure 4).

5. Conclusions

Feeding of European grayling larvae during the period of its transition to external nutrition with nauplia artemia, enriched with lactobacilli *Lactobacillus casei* IMV B-7280 ensures acceleration of growth processes.

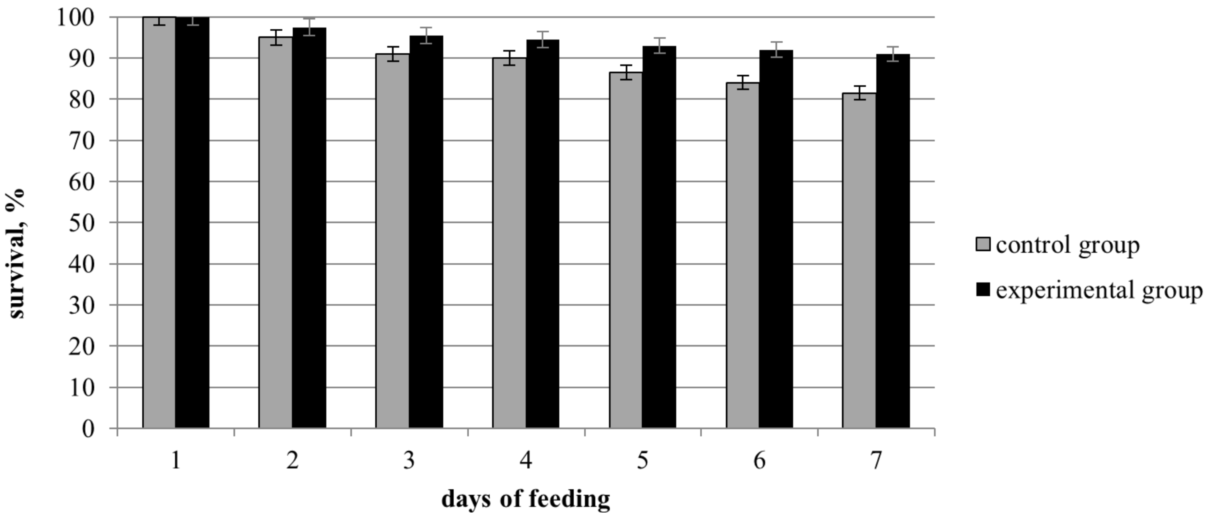

Figure 4. Dynamics of European grayling larvae survival under conditions of live feeds of adding live feed to the diet.

Introduction of *Daphnia magna* culture, previously received of co-cultivation with microalgae *Desmodesmus armatus* with addition of trehalose lipids, into a growing grayling larvae ration, contributes to reducing the mortality of young fish and accelerating its growth rate.

The usage of lactic acid probiotic microorganisms *Lactobacillus casei* IMV B-7280 for incapsulation in artemia nauplia, and also the procedure of co-cultivation live feeds with microalgae in in the presence of biosurfactants, may be appropriate for young fish feeding, but the effectiveness of these procedures has to be investigated for each specific species separately.

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References

[1] El-Saadony M T, Alagawany M, Patra A K, Kar I, Tiwari R, Dawood M A O, Dhama K and Abdel-Latif H M R 2021 *Fish & Shellfish Immunology* **117** 36–52 ISSN 1050-4648 URL https://doi.org/10.1016/j.fsi.2021.07.007
[2] Dawood M A, Koshio S, Abdel-Daim M M and Van Doan H 2019 *Reviews in Aquaculture* **11**(3) 907–924 URL https://doi.org/10.1111/raq.12272
[3] Qin C, Xie Y, Wang Y, Li S, Ran C, He S and Zhou Z 2018 *Frontiers in Physiology* **9** ISSN 1664-042X URL https://doi.org/10.3389/fphys.2018.01245
[4] Zhang Z, Lv J, Pan L and Zhang Y 2018 *Applied Microbiology and Biotechnology* **102** 8135–8143 ISSN 1432-0614 URL https://doi.org/10.1007/s00253-018-9217-9
[5] Pereira W A, Mendonça C M N, Urquiza A V, Marteinsson V Þ, LeBlanc J G, Cotter P D, Villalobos E F, Romero J and Oliveira R P S 2022 *Microorganisms* **10**(9) 1705 ISSN 2076-2607 URL https://doi.org/10.3390/microorganisms10091705
[6] Ishthiaq I, Ahmed J and Ramalingam K 2021 *Biointerface Research in Applied Chemistry* **11**(6) 14697–14708 URL https://doi.org/10.33263/BRIAC116.1469714708
[7] Dhont J, Dierckens K, Støttrup J, Van Stappen G, Wille M and Sorgeloos P 2013 5 - Rotifers, Artemia and copepods as live feeds for fish larvae in aquaculture *Advances in Aquaculture Hatchery Technology* Woodhead Publishing Series in Food Science, Technology and Nutrition ed Allan G and Burnell G (Woodhead Publishing) pp 157–202 ISBN 978-0-85709-119-2 URL https://doi.org/10.1533/9780857097460.1.157
[8] Gogoi B, Safi V and Das D 2016 *Research Journal of Animal, Veterinary and Fishery Sciences* **4**(3) 7–12 URL http://www.isca.in/AVFS/Archive/v4/i3/2.ISCA-RJAVFS-2016-006.php
[9] Cios S, Grudniewska J, Witkowski A and Kotusz J 2018 *Lipień* (Olsztyn: Wyd. IRS)
[10] Sorgeloos P, Dhert P and Candreva P 2001 *Aquaculture* **200**(1) 147–159 ISSN 0044-8486 advanced Biotechnology in Hatchery Production URL https://doi.org/10.1016/S0044-8486(01)00698-6
[11] Cheban L, Grynko O and Dorosh I 3918 *Fisheries & Aquatic Life* **26** 57–64 URL https://doi.org/10.2478/aopf-2018-0007
[12] Kucheruk A, Hrytsyniak I, Mruk A and Velykopolsky I 2015 *Ribogospod. nauka Ukr.* (2(32)) 31–40 URL https://doi.org/10.15407/fsu2015.02.031
[13] Kucheruk A, Mruk A and Buzevitch I 2018 *Ribogospod. nauka Ukr.* (3(45)) 28–38 URL https://doi.org/10.15407/fsu2018.03.028
[14] Müller E and Radler F 1993 *Folia Microbiologica* **38**(6) 441–446 ISSN 1874-9356 URL https://doi.org/10.1007/BF02814392
[15] Napiórkowska-Krzebietke A 2017 *Journal of Elementology* **22**(3) 831–41 URL https://doi.org/10.5601/jelem.2016.21.4.1375
[16] Brown M R and Blackburn S I 2013 4 - Live microalgae as feeds in aquaculture hatcheries *Advances in Aquaculture Hatchery Technology* Woodhead Publishing Series in Food Science, Technology and Nutrition ed Allan G and Burnell G (Woodhead Publishing) pp 117–158e ISBN 978-0-85709-119-2 URL https://doi.org/10.1533/9780857097460.1.117

[17] Pirog T P and Konon A D 2014 *Biotechnologia Acta* **7**(1) 9–30 URL https://doi.org/10.15407/biotech7.01.009
[18] Khuda L, Andrushchak M, Lubenets V, Karpenko O, Pokynbroda T, Semeniuk I and Khudyi O 2021 *Biolohichni systemy* **13**(1) 9–13 URL https://archer.chnu.edu.ua/xmlui/handle/123456789/3118

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Heap leaching of gold from the destructured oxidized ore of the Belsu deposit, Republic of Kazakhstan

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Heap leaching of gold from the destructured oxidized ore of the Belsu deposit, Republic of Kazakhstan

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Abstract. Heap leaching technology is increasingly being used to extract metals from poor ores, especially in the gold mining industry and is characterized by low capital costs compared to other methods. The purpose of this work is to develop modes and indicators of heap leaching of gold from the destructured oxidized ore of the Belsu deposit, Kazakhstan. The material composition of the ore has been studied, studies of percolation and pelletizing modes have been carried out. For the first time, studies on heap leaching for oxidized ore of the Belsu deposit (Kazakhstan) were conducted. It has been established that gold is well extracted by heap leaching from ore crushed to -25 mm and -12 mm after preliminary pelletizing. The degree of dissolution of gold from ore with a size of -25 mm and -12 mm has similar values – 74.41% and 76.57%, respectively. The leaching tails contain 0.478 g/t and 0.440 g/t gold. The consumption of sodium cyanide did not exceed 0.47 kg/t. The expected extraction of gold into the Dore alloy will be 66.60-68.53% with an initial gold content of 1.87-1.88 g/t in the ore. According to the developed technology, an industrial plant for heap leaching of gold from oxidized ore of the Belsu deposit was built.

1. Introduction

Heap leaching technology is increasingly being used to extract metals from poor ores, especially in the gold mining industry and is characterized by low capital costs compared to other methods. For many decades, the demand for heap leaching has been growing due to its environmental advantages [1–5]. The long-term practice of foreign plants using this technology confirms their high technical and economic efficiency [4–10].

However, a big problem is the destructured and clay ores, which reduce the seepage of the gold-dissolving solution, which leads to decrease of gold extraction [11–15]. Based on the extensive experience of heap leaching operations, agglomeration of crushed ore can be successfully considered and used as a pretreatment of ore that contains a significant amount of fines and clay minerals [14–21].

The purpose of this work is to develop modes and indicators of heap leaching of gold from the destructured oxidized ore of the Belsu deposit, Kazakhstan with recommendations for use on an industrial scale.

2. Experiment

2.1. Materials

The gold-bearing ore of the Belsu deposit in the Abay district, Abay region, Republic of Kazakhstan was studied (figure 1). The technological sample is represented by two types of ores in terms of physical structure: destructured weathering crust (sometimes clumped together) and strong quartz-containing pieces of ore, the number of which is much smaller by weight.

Figure 1. General view of the ore deposit.

2.2. Methods

According to the results of assay analysis, the average gold content in the ore is 1.88 g/t. The chemical composition of the ore is shown in table 1.

The industrial value in the sample is gold. Other metals are contained in insignificant quantities and are out of interest for industrial production. Arsenic is practically absent, and the antimony content was 0.082%. The sample belongs to a poor sulfide type of ore (Sulfide < 1%). According to the degree of oxidation, the sample is assigned to the oxidized zone. The results of wet sieve analyses of a crushed sample with a size of -25 mm and -12 mm are shown in figures 2-4.

The visual determination of a large amount of destructured ore in the sample was confirmed by the results of the sieve analysis. According to the physical condition, the initial ore sample (and even more crushed ore) is highly destructured. The amount of fine grade (-2.5 mm) in the crushed sample of -25 mm and -12 mm was 82-83%. This will create serious problems for leaching solutions to seep through the ore stack during heap leaching.

Table 1. Chemical composition of gold-bearing ore of Belsu deposit.

Components	Content, %	Components	Content, %
Copper	0.037	Potassium oxide	1.37
Nickel	0.003	Silicon oxide	57.42
Cobalt	0.013	Aluminum oxide	16.40
Zinc	0.041	Arsenic	0.02
Lead	0.042	Antimony	0.082
Iron	5.66	Total sulfur	0.43
Calcium oxide	1.75	Sulphate sulfur	0.40
Magnesium Oxide	1.10	Sulfide sulfur	0.03
Sodium oxide	0.59	Degree of sulfur oxidation	93.02

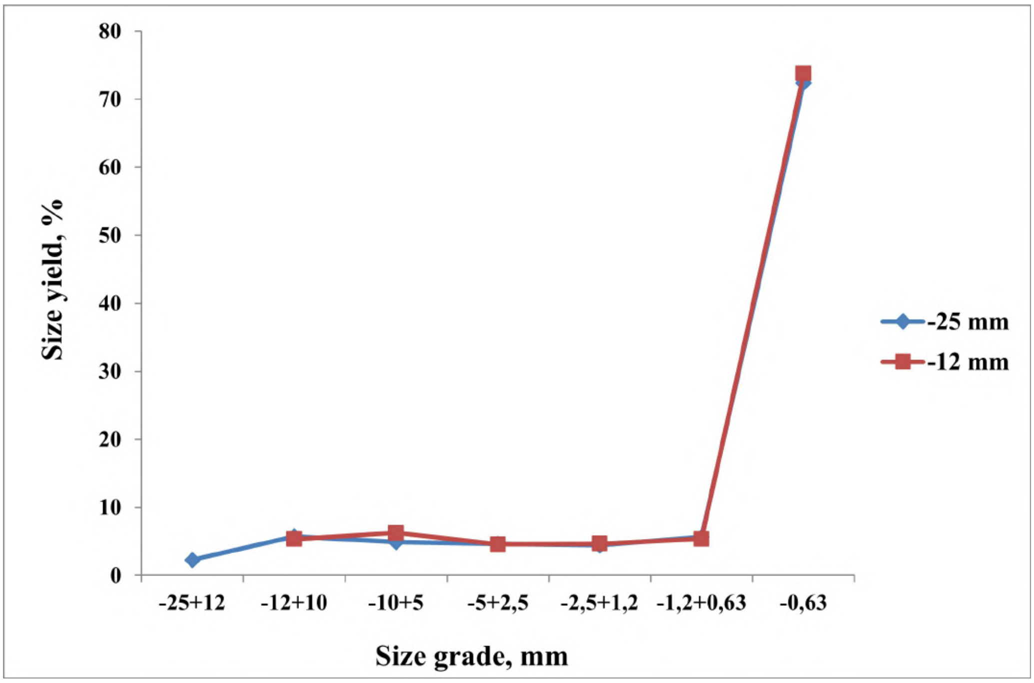

Figure 2. Granulometric characteristics of crushed ore.

2.2.1. Laboratory tests of cyanide leaching of gold. To evaluate the type of the gold in the ore, standard bottle tests were carried out on crushed ore with a grain size of 90% of the -0.071 mm class. To assess the change in the degree of dissolution of gold with an increase in the size of the ore, an additional bottle test is carried out on crushed ore with a size of -2.5 mm.

Laboratory studies on cyanide leaching were carried out in a bottle agitator with a rotation speed of 30 rpm. The modes of leaching were as follows: the mass of ore samples for each experiment was 300 g, the ratio Solid:Liquid = 1:2, pH 10-11, the concentration of sodium cyanide was 0.100%, the duration of leaching was 24 hours. During the leaching process, the concentration of sodium cyanide and the pH of the solution were monitored, reagents were added if necessary.

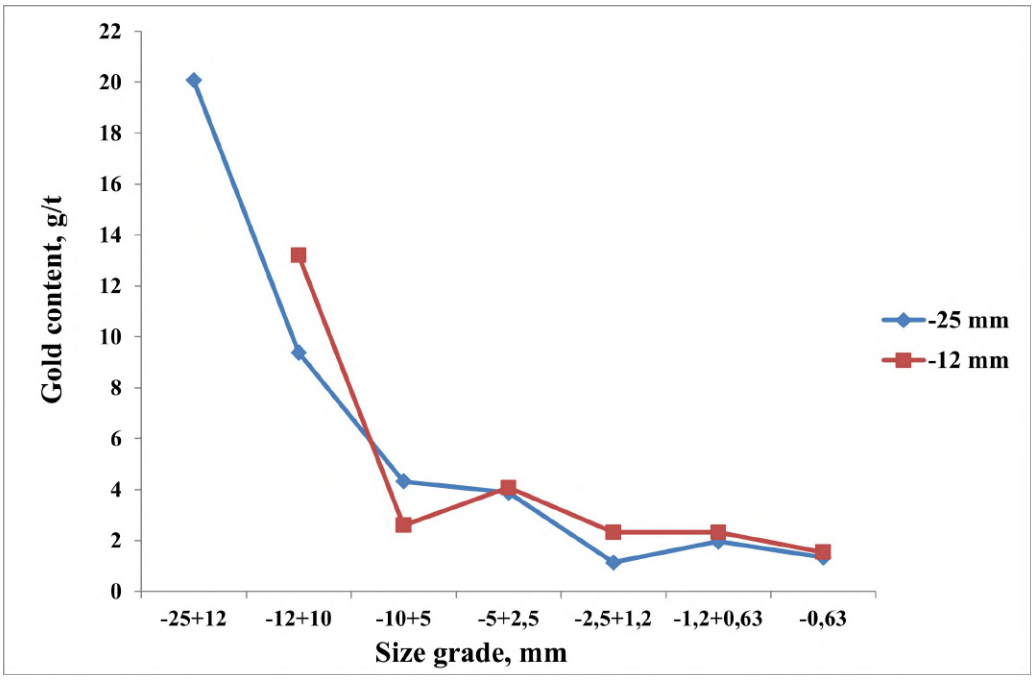

Figure 3. Change in gold content for ore of various sizes by class.

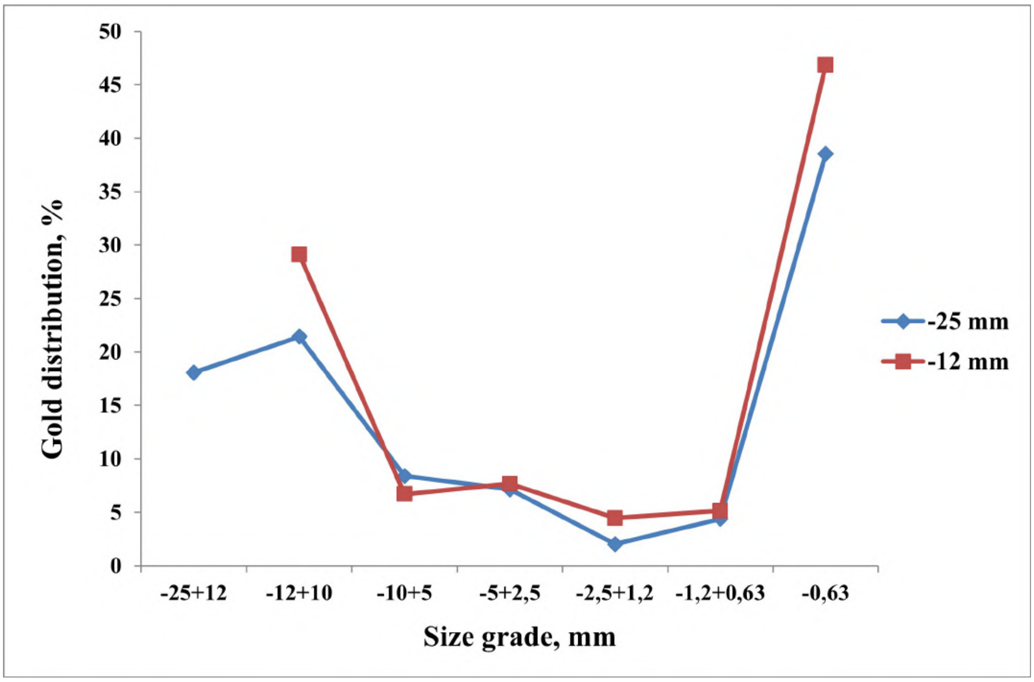

Figure 4. Distribution of gold for ore of various sizes by class.

2.2.2. Determination of percolation characteristics of the initial non-pelletized ore. In world practice, when the ore size is less than 12 mm, as a rule, preliminary pelletizing of the ore with cement is carried out before stacking it. Pelletizing is carried out in agglomerating devices of various types. All this requires certain material costs and increases the cost of gold production [6,14,15,19]. In this regard, the possibility of using non-pelletized raw materials was tested by determining its percolation properties.

To test the possibility of using non-pelletized ore for heap leaching, percolation tests of ore samples with a size of -25 and -12 mm, i.e. the size that will be used during column tests, were carried out.

Percolation tests were carried out in a column with a diameter of 97 mm and a height of 515 mm. The column was filled with 5.0 kg of ore, its compaction was performed by shaking, water was poured from the bottom up, the degree of shrinkage of the ore was determined after soaking, after holding for 2 hours and additional shaking, the maximum percolation rate of water through the ore layer was determined.

2.2.3. Research on the technology of heap leaching of gold. Studies on the technology of heap leaching of gold were carried out in columns. Heap leaching of gold in columns was carried out in a closed cycle: leaching of gold from ore with alkaline cyanide solutions; sorption of dissolved gold with a sorbent; return of the solution to leaching after adjusting the concentration of sodium cyanide and pH.

Anion exchange resin AM-2B was used as a sorbent for the extraction of dissolved gold from productive solutions. The choice of ion exchange resin as a sorbent is due to the presence of a large number of fine sludge particles in the ore of the Belsu deposit. When using activated carbon, thin sludge particles will have a negative effect on resin, reducing its sorption activity.

The installation for conducting column tests included 2 columns for leaching gold from ore:

- for ore size -25 mm: the diameter of the leaching column is 260 mm; the height of the column is 2420 mm; the height of the ore layer in the column is 2420 mm. The mass of ore in the column by dry weight is 136.97 kg.
- for ore size -12 mm: the diameter of the leaching column is 253 mm; the height of the column is 2410 mm; the height of the ore layer in the column is 2410 mm. The mass of ore in the column by dry weight is 137.46 kg.

Solutions of 0.05% (0.5 g/l) sodium cyanide were used as a leaching solution, the pH was maintained in the range of 10.5-11.0 due to the addition of sodium hydroxide.

3. Results and discussion

The results of bottle tests of cyanide leaching of gold are presented in table 2.

Table 2. Results of bottle tests of cyanide leaching of gold from samples of various sizes.

Name of parameters	-2.5 mm		90 % -0.071 mm	
	1	2	1	2
Au content in the liquid phase of the pulp, mg/l	0.77	0.79	0.95	1.04
Au content in the solid phase of tails, g/t	0.28	0.28	0.10	0.12
Estimated Au content in ore, g/t	1.82	1.86	2.00	2.20
Degree of dissolution Au, %	84.62	84.95	95.00	94.55

The results of bottle tests of cyanide leaching of gold from crushed ore (90% -0.071 mm) confirmed that the gold in the ore is mainly in free form, the degree of dissolution of gold from the crushed sample reached 94.5-95%.

From a crushed sample with a size of -2.5 mm, 84.62–84.94% (average 84.79%) of gold is dissolved, i.e. it decreases by 10%, but this decrease is not drastic and assumes fairly good indicators for heap leaching.

The consumption of sodium cyanide for interaction with minerals was 0.84-1.80 kg/t.

The results of percolation tests of crushed ore are shown in table 3.

Table 3. Results of tests on percolation of crushed ore.

Name of indicators	-25	-12
Degree of shrinkage of the ore after soaking, %	0.42	0.63
Degree of shrinkage of the ore after soaking and shaking with water, %	0.84	1.25
Percolation rate of water through the ore layer, m/h	0.01	0.01

The degree of shrinkage of the ore after soaking and shaking with water for both sizes met the requirements of the guidelines (no more than 10%), and the percolation rate of water through the ore layer is many times lower than the regulated one (at least 10 m/h). Ore without preliminary pelletizing is not suitable for heap leaching.

Pelletizing modes have been developed to conduct the heap leaching process. Portland cement of the M-400 D20 GOST 10178-85 grade was used as a binder for pelletizing ore. The results of tests to determine the optimal consumption of Portland cement are shown in tables 4, 4.

Table 4. Determination of optimum Portland cement consumption for pelletising -25 mm crushed ore.

Added Portland cement during granulation, kg/t	10	18	22
Added water during pelletizing, l/t	176.0	190.7	181.9
Ore moisture after pelletizing, %	16.71	17.59	16.94
Percolation rate of water through a layer of granular ore, m/h	46.42	60.93	60.93
Degree of destruction of granules after percolation test, %	28	5	3

Table 5. Determination of optimum Portland cement consumption for pelletising -12 mm crushed ore.

Added Portland cement during granulation, kg/t	10	18	22
Added water during pelletizing, l/t	184.8	196.5	205.3
Ore moisture after pelletizing, %	17.31	17.98	18.49
Percolation rate of water through a layer of granular ore, m/h	17.41	60.93	60.93
Degree of destruction of granules after percolation test, %	30	5	3

All regulatory parameters of percolation for ore with a grain size of -25 mm and -12 mm are satisfied by the following modes: portland cement consumption of 18 kg/t; water consumption of 190.7 l/t (for a grain size of -25 mm) and 196.5 l/t (for a grain size of -12 mm); humidity of granules is about 18%.

Two column tests were carried out, with preliminary pelletizing of ore with a consumption of Portland cement of 18 kg/t. Figure 5 shows the obtained granules.

The results of studies on heap leaching of gold from pelletized ore are presented in figures 6-8.

To dissolve gold, 31 leaching cycles were required for ore with a grain size of -25 mm and 32 cycles for ore with a grain size of -12 mm. The total amount of productive solution to achieve complete leaching was 2.192-2.296 m^3/t.

-25 mm

-12 mm

Figure 5. Pelletized ore -25 mm and -12 mm

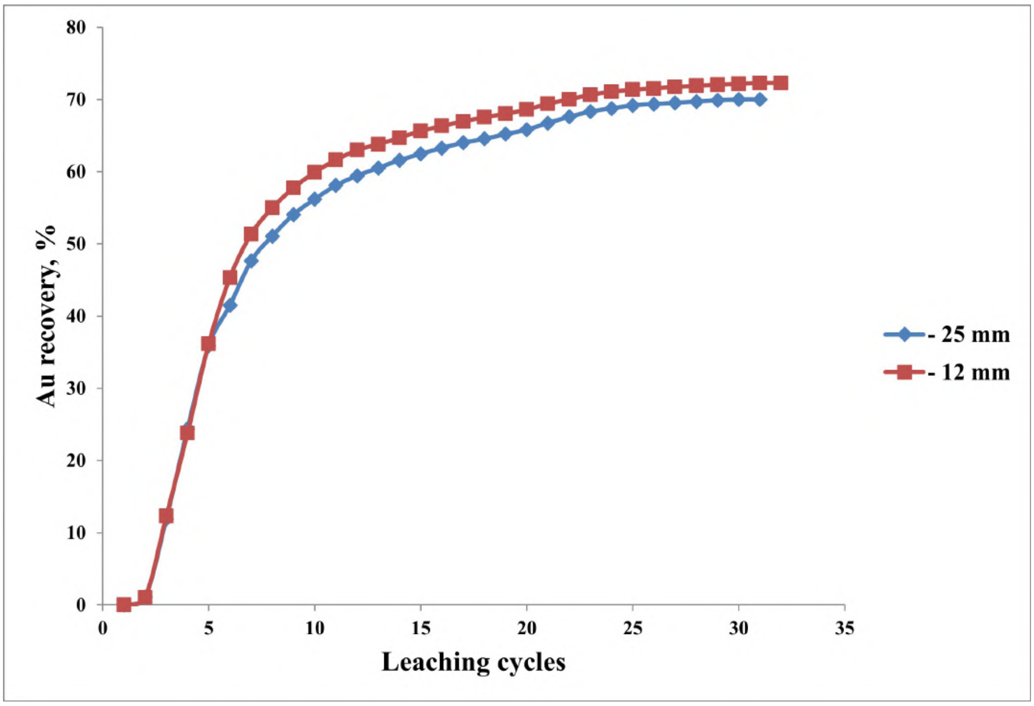

Figure 6. Dependence of gold extraction on the duration of leaching.

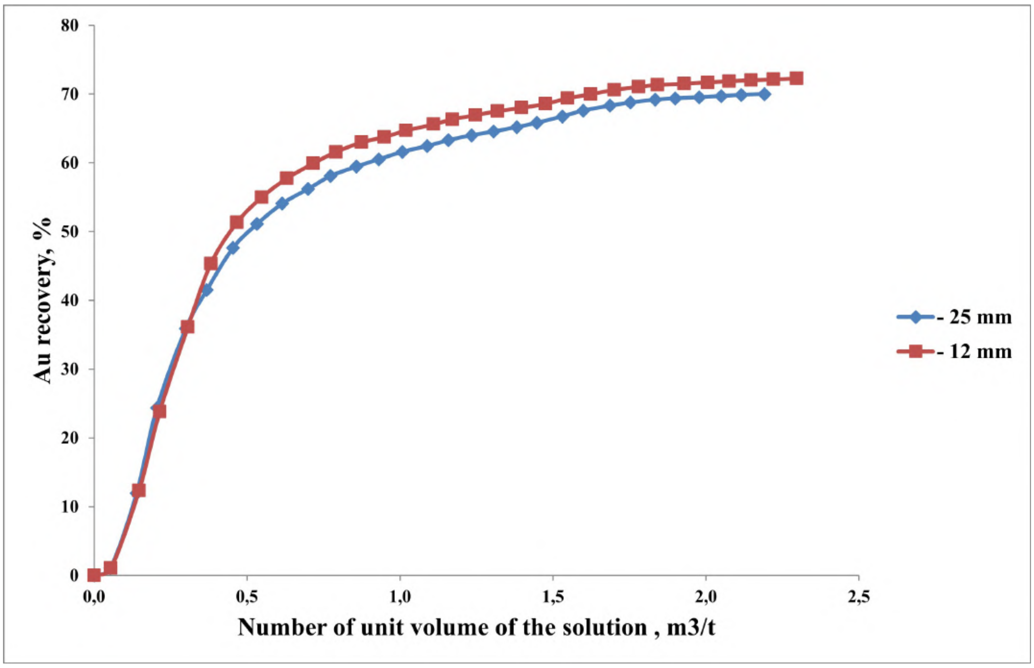

Figure 7. Dependence of gold extraction on the amount of solution passed.

The consumption of sodium cyanide did not exceed 0.47 kg/t, the consumption of sodium hydroxide was 0.150-0.147 kg/t. The gold content in the leaching tailings is 0.478 g/t and 0.440 g/t. Based on the data obtained, the gold balance was calculated during heap leaching of gold from the ore of the Belsu deposit (table 6).

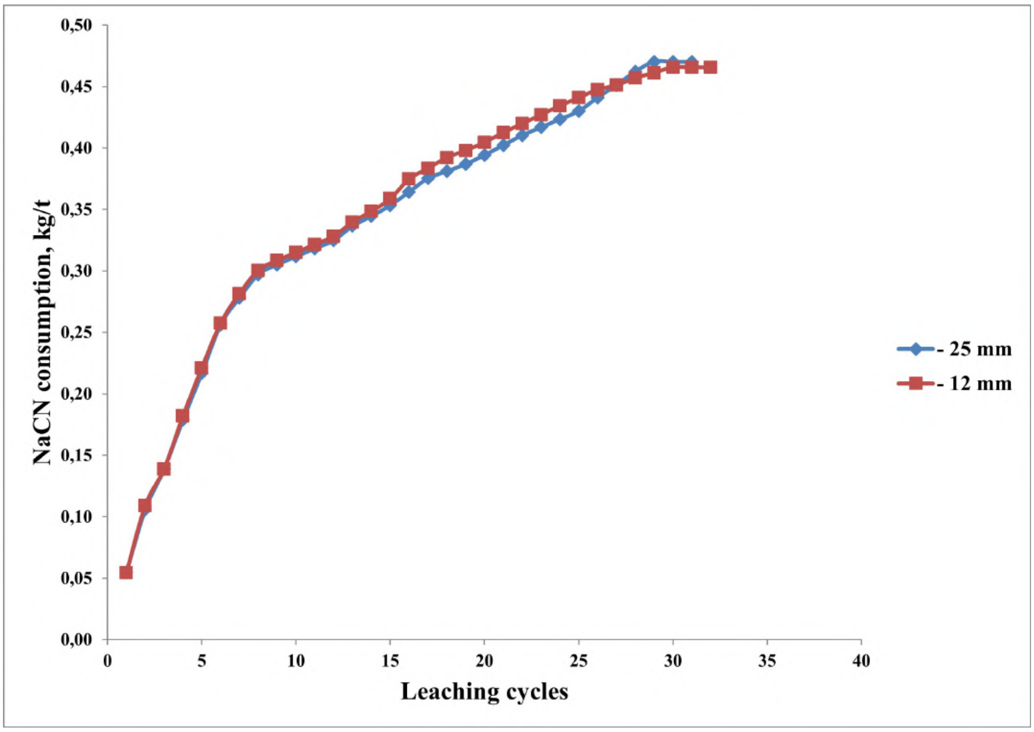

Figure 8. Sodium cyanide consumption during leaching

Table 6. Gold balance during column tests on heap leaching of gold.

Name of indicators	-25	-12
Gold extracted by ion-exchange resin, g/t of ore	1.381	1.429
Gold extracted by ion-exchange resin, %	74.02	76.09
Gold extracted at the water washing operations, g/t of ore	0.003	0.005
Gold brought with the analyzed solutions, g/t of ore	0.004	0.004
Gold content in column leaching tailings, g/t	0.478	0.440
Calculated gold content in the initial ore, g/t	1.866	1.878
Degree of gold dissolution from ore by balance, %	74.41	76.57
Expected gold extraction into commercial product – Doré bars, %	66.60	68.53

From ore, gold is satisfactorily dissolved during heap leaching. According to the balance, the degree of dissolution of gold from ore was 74.41-76.57%.

The obtained high technological indicators of column tests indicate that the oxidized ore of the Belsu site can be efficiently processed by heap leaching with preliminary pelletizing with cement.

According to the research results, technological regulations have been developed and an industrial plant for heap leaching of gold from the ore of the Belsu deposit has been built.

4. Economic of production

The total investment in the organization of the production site at the Belsu field amounted to 8 million US dollars. At the market price of gold of 1800 US dollars per 1 troy ounce, the total revenue will be 147.7 million US dollars. All in-sustaining costs 1042 US dollars per troy ounce of gold. The project implementation period with an annual output of 500 thousand tons of ore will be 6 years. The net present value for the period of the project implementation at a discount rate of 15% will amount to 24.8 million US dollars. The investment return period is 1 year.

5. Conclusions

The gold-bearing ore of the Belsu deposit is extremely destructured. The amount of class -2.5 mm limiting percolation during heap leaching was 82-83%. Processing of ore of such granulometric composition by heap leaching technology is impossible.

We have developed ore processing modes of the Belsu deposit with preliminary pelletizing. Cement consumption was 18 kg per 1 ton of ore. The degree of dissolution of gold from ore with a size of -25 mm and -12 mm has similar values – 74.41% and 76.57%, respectively. The leaching tails contain 0.478 g/t and 0.440 g/t gold, respectively. The consumption of sodium cyanide did not exceed 0.47 kg/t. The consumption of sodium hydroxide was 0.150-0.147 kg/t during gold leaching. The volume of passed solutions for complete leaching of gold was 2.192-2.296 m^3/t of ore, which characterizes a fairly good kinetics of gold dissolution. The expected extraction of gold into the Dore alloy during processing of the ore of the upper oxidized zone under industrial conditions will be 66.60-68.53% with an initial gold content of 1.87-1.88 g/t in the ore.

For industrial conditions of heap leaching, it is recommended to use the ore of the Belsu deposit with a size of -25 mm with its preliminary pelletizing with cement. The developed technology made it possible to efficiently process this ore and obtain gold in the form of marketable products – the Dore alloy. The economic calculation confirmed the effectiveness of the developed technology, the technology has been introduced into industrial production.

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References

[1] Fleming C A 1992 *Hydrometallurgy* **30**(1) 127–162 URL `https://doi.org/10.1016/0304-386X(92)90081-A`
[2] Kappes D W 2002 Precious Metal Heap Leach Design and Practice *Mineral Processing Plant Design, Practice, and Control* vol 1 pp 1606–1630 ISBN 0873352238 URL `https://ore-max.com/pdfs/resources/precious_metal_heap_leach_design_and_practice.pdf`
[3] Thenepalli T, Chilakala R, Habte L, Tuan L Q and Kim C S 2019 *Sustainability* **11**(12) 3347 URL `https://doi.org/10.3390/su11123347`
[4] Petersen J 2016 *Hydrometallurgy* **165** 206–212 URL `https://doi.org/10.1016/j.hydromet.2015.09.001`
[5] Ghorbani Y, Franzidis J P and Petersen J 2016 *Mineral Processing and Extractive Metallurgy Review* **37**(2) 73–119 URL `https://doi.org/10.1080/08827508.2015.1115990`
[6] Shalgymbayev S T, Bolotova L S and Surimbayev B N 2021 *Tsvetnye Metally* (9) 38–45 URL `https://doi.org/10.17580/tsm.2021.09.03`
[7] Trexler D T, Flynn T and Hendrix J L 1990 *Geo-Heat Center Quarterly Bulletin* **12** 1–4 URL `https://data.nbmg.unr.edu/public/Geothermal/GreyLiterature/Trexler_HeapLeaching_1990.pdf`
[8] Yessengarayev Y K, Baimbetov B S and Surimbayev B N 2020 *Non-ferrous Metals* (2) 25–30 URL `https://doi.org/10.17580/nfm.2020.02.04`
[9] Sánchez-Chacón A E and Lapidus G T 1997 *Hydrometallurgy* **44**(1) 1–20 URL `https://doi.org/10.1016/S0304-386X(96)00052-7`

[10] van Staden P and Petersen J 2021 *Minerals Engineering* **168** 106915 URL https://doi.org/10.1016/j.mineng.2021.106915
[11] Kapur P C and Runkana V 2003 *International Journal of Mineral Processing* **72**(1) 417–427 URL https://doi.org/10.1016/S0301-7516(03)00116-9
[12] Toro N, Ghorbani Y, Turan M D, Robles P and Gálvez E 2021 *Metals* **11**(10) 1539 URL https://doi.org/10.3390/met11101539
[13] Baigenzhenov O, Khabiyev A, Mishra B, Aimbetova I, Yulusov S, Temirgali I, Kuldeyev Y and Korganbayeva Z 2022 *Recycling* **7**(6) 85 URL https://doi.org/10.3390/recycling7060085
[14] Bouffard S C 2005 *Mineral Processing and Extractive Metallurgy Review* **26**(3-4) 233–294 URL https://doi.org/10.1080/08827500590944009
[15] Bouffard S C 2001 *Metallurgical and Materials Transactions B* **32** 763–776 URL https://doi.org/10.1007/s11663-001-0063-1
[16] Dhawan N, Safarzadeh M S, Miller J D, Moats M S and Rajamani R K 2013 *Minerals Engineering* **41** 53–70 URL https://doi.org/10.1016/j.mineng.2012.08.013
[17] Bouffard S C and West-Sells P G 2009 *Hydrometallurgy* **98**(1) 136–142 URL https://doi.org/10.1016/j.hydromet.2009.04.012
[18] Martens E, Zhang H, Prommer H, Greskowiak J, Jeffrey M and Roberts P 2012 *Hydrometallurgy* **125-126** 16–23 URL https://doi.org/10.1016/j.hydromet.2012.05.005
[19] Bouffard S C 2008 *Minerals Engineering* **21**(15) 1115–1125 URL https://doi.org/10.1016/j.mineng.2008.02.010
[20] Kodali P, Dhawan N, Depci T, Lin C L and Miller J D 2011 *Minerals Engineering* **24**(13) 1478–1487 URL https://doi.org/10.1016/j.mineng.2011.07.010
[21] McBride D, Gebhardt J E, Croft T N and Cross M 2016 *Minerals Engineering* **90** 77–88 URL https://doi.org/10.1016/j.mineng.2015.11.005

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Indicators improvement of territories spatial development

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Indicators improvement of territories spatial development

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Abstract. Land use planning of territorial communities is an important component of creating rational sustainable land use. The key task of planning is to find a balance between the economic and ecological components of land use. The most effective agricultural land on the territory of communities is arable land. Advanced modern software and the remote zoning data amount of land make it possible to conduct a complete analysis of land resources condition. To evaluate project decisions, plan indicators and determine land use trends, it is necessary to use integrated indicators that comprehensively describe spatial characteristics. On the basis of complex numbers, it is offered to use an indicator that consists of the territory assessment arableness and the area of land massifs to the perimeter ratio. For the assessment, a "reference" project is used, which was created taking into account the developed recommendations. The integration of the indicator makes it possible to indirectly evaluate the ecological and economic component of agricultural activity. The use of complex numbers makes it possible to expand the use of analysis tools and the capabilities of computing technology.

1. Spatial development planning in Ukraine

The land reform began in 1990 and was a continuation of the constant search for rational use of land from the previous period. As a result of these searches, the use of land resources is currently planned at the level of territorial communities. The main technical planning document is the Comprehensive Spatial Development Plan. Also, the calculation of the normative monetary valuation of land, which affects the amount of rent and the calculation of land tax, will be carried out in the future on the territory of territorial communities. There are projects that will use the territorial community as a unit for conducting land management works (inventory of land and natural resources) during the planning of territorial communities' spatial development. Indicators of land resources use should be objective and include as many indexers as possible related to the spatial characteristics of the territory [1]. Unfortunately, modern indicators are mainly focused on the land ratio. The indicators need some improvement based on the characteristics of the territory organization. When planning the use of land resources, there are many project options, and which option to apply depends on the calculated indicators, which should comprehensively characterize economic activity.

The use of land resources, as the main spatial basis and means of production, depends on the planning and design efficiency. Planning is based on evaluations of project decisions, which in turn depend on criteria [2]. Currently, such indicators of land resources use as arable land, agricultural development, the coefficient of anthropogenic load, the coefficient of territory ecological stability are very popular. But the use of these indicators has both positive and negative impacts. The positives include the fact that these indicators are intuitive and can be easily compared. The negatives include the fact that all indicators do not take into account the spatial placement of objects, but only fix their ratio [3]. It should be noted that indicators (indices) that characterize the spatial relationship of land exist and include: the index of the standard deviation of the counter size, the shape index, the index of the average distance between contours, the fragmentation index, etc. But all these indices are more related to the study of landscapes and to a lesser extent to agricultural activities. They also have their positive and negative sides of application. The positives include the fact that they are very closely correlated with each other. The negatives include the fact that these indicators separately are not very informative.

Indices of spatial development are evolved for many programs in different countries of the world: Poland, Spain, Taiwan, Norway, etc. Sowińska-Świerkosz and Soszyński [4] conducted a review of the relevant literature (102 articles), which allowed to choose the most similar indices of the rural areas study: an index that covers rural areas with a high risk of urbanization, an indicator of the rural areas viability, and an index of the land strategic location. Metrics used to analyze the spatial aspects of rural urbanization and those related to sustainability proved to be the most effective. The study [5] developed the Index of Prognosis Rural Landscape Preferences (IPRLP), which consists of nine variables relating to the presence or percentage of various landscape attributes. Nogués et al [6] investigated the possibility of using stability indicators to determine and measure the quantitative and qualitative spatial stability of territories. The essence of the study was to combine social, economic, environmental and spatial indicators into a single local index using robust principal component analysis and a multi-criteria decision-making method. Chang et al [7] applied the two-dimensional local indicator of spatial autocorrelation (BiLISA) to determine the spatial distribution of synergies and trade-offs between different co-benefits. The research paper [8] defines planning tools for the protection of arable land. Factors and prerequisites of spatial planning indicators are analyzed. Barneveld et al [9] evaluated the use of the connectivity index to evaluate anti-erosion measures.

2. Application of spatial development complex indicators

Economic activity is a complex ecological and economic process, and therefore we suppose it appropriate to consider the use of more complex indicators. The indicators, indices and coefficients listed above are displayed as real numbers. Although mathematical sciences, computer technology has taken a big step forward and researchers for spatial planning have the opportunity to use mathematical objects more complex than real numbers. For example, complex numbers that can more deeply describe various factors of planning or designing the land resources use. It can be determined that scientists divide ecological, economic and social aspects of agricultural activity, as well as their ecological-economic, socio-economic, etc. integrations. To reflect such project evaluation criteria, an indicator can be used that will simultaneously take into account environmental and economic factors. It is rather difficult to directly compare environmental and economic indicators.

As a rule, ecological indicators are converted into economic indicators by calculating the amount of funds necessary to prevent the manifestation of negative natural and anthropogenic phenomena. It should be noted that economic indicators have a limited scope, because there are such phenomena as inflation, currency devaluation, etc. This forces the use of discounting methods. Also, economic processes are affected by changes in market conditions and other factors that limit long-term forecasts and the use of economic indicators that were taken into account due to environmental ones. Therefore, we suggest using the ratio of arable land to the entire area as an ecological indicator. Arable land is intensively used, while the natural environment is deteriorating [10]. Ecologically stabilizing lands have a positive effect on arable land: water bodies, natural fodder lands, forested areas.

As a technical indicator that affects economic costs, usage the ratio of the area of arable land contours to the perimeter. This indicator takes into account the spatial location of agricultural production various objects. We suggest making calculations in complex numbers, which will make it possible to combine various aspects of economic activity. The number $a + bi$, where a and b are any real numbers, i is an imaginary unit, is called a complex number (a is the real part, bi is the imaginary part of the complex number, and b is the coefficient of the imaginary part). The real part will take into account territory, and the coefficient for the imaginary part will calculate the spatial indicator, which is the sum of the area to the perimeter ratios. Thus, our indicators will take into account both the ecological part and spatial characteristics.

Spatial indicators of forecasting the use of land resources are in the fact that there are dependencies on the shape of fields and working areas and various economic effects [11]. The economic efficiency of economic activity depends on various costs, one of which is the fuel and oil cost and agricultural machinery depreciation. This is due to those idle runs and turns of agricultural machinery. That is, the shape of the field affects the amount of expenses. In turn, costs are part of the economic component. Indicators of the intensively used land and ecologically stabilizing land ratio do not take into account economic effects. With the same land ratio, the ecological effect can be different. Different configurations of fields and working areas can create more protected areas from negative natural and anthropogenic phenomena. In figure 1, we see 3 schematic views of the arable land configuration with ecologically stabilizing lands. Yellow color shows conditionally arable land, green shows ecologically stabilizing land, purple shows positive impact on arable land. By positive influence we mean anti-erosion protection, creation of microclimatic conditions for the growth of agricultural crops, etc. All three schematic options have the same land ratio. Plowability is 50%. Regarding the ease of working areas use, option A is better, option B is somewhat worse. Option C is not suitable for the use of powerful agricultural machinery at all. Regarding the impact on arable land, option C provides the best impact due to the mosaic structure of the territory. Option A has the minimum influence area.

On the one hand, the high contour and fragmentation of the territory creates biological diversity, provides greater protection against wind and water erosion, and provides a stronger interaction between ecologically stabilizing lands and intensively used lands. On the other hand, high contouring worsens the use of agricultural machinery due to idle turns, increases the costs of fuel and oil and work time (increase in wage costs), amortization, wear and tear of agricultural machinery, etc [12]. Thus, we need to find a balance between the economic and ecological components of land resources use. When designing, as a rule, several options are formed according to different rules, which in turn arise due to the fact that there are no universal ideal management conditions. There are always many factors and many options to consider. At the final stage of planning, these projects are evaluated and the best one is selected. If we use only the land ratio indicator, there is no economic evaluation of the project. If we use only economic indicators, there will be no information on environmental safety. Therefore, our offered indicator based on complex numbers will at least indirectly contain both components. This will make it possible to more objectively and qualitatively find the best option for spatial planning of land resources [13]. Land use is central to addressing food security, including biodiversity conservation, climate change, sustainability issues, sustainable energy, achieving social justice, and poverty alleviation.

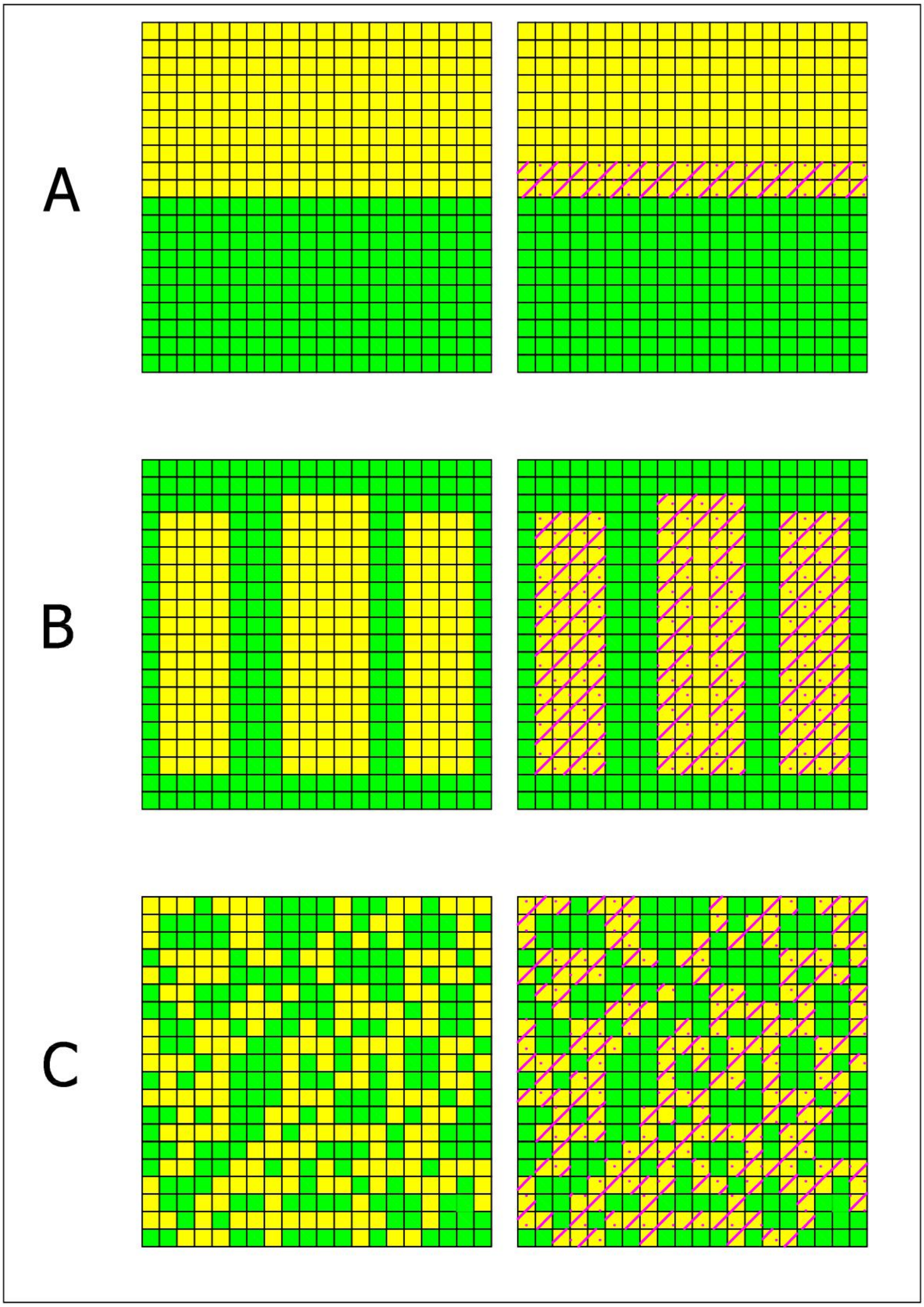

Figure 1. Options of spatial development comprehensive assessment.

To calculate the "reference" complex indicator, the 2013 recommendations of the Derzhkomzem (State Committee of Ukraine on Land Resources) were used regarding the ecological and economic substantiation of land management and the introduction of crop rotation. These recommendations suggest that the shape of the field be rectangular or trapezoidal, have parallel sides, an aspect ratio of 1 to 5, and be located, if possible, from north to south with long sides. The area of the field should be up to 400 hectares. Field protection forest strips should be located along the boundaries of the working plots, entrances to each land plot should be provided. Field protection forest strips should be located at an angle of 90 degrees in relation to harmful winds (with a deviation of up to 30 degrees).

With the help of the software, a "reference" project was designed and the sum of perimeter and area ratio was determined. The considered perfect conditions do not take into account the relief, variegation of the ground cover, etc. For the calculation, we used an area of 1000 hectares with a plowing rate of 50%. In scientific sources, researchers have come to a consensus that the rate of plowing is too high for Ukraine and should be reduced. But there is no agreed exact data on the size of the plowability indicator.

Next, using our example, we calculate how much the complex number of the "reference" project differs from the corresponding options. We make a general conclusion, which option is the best. For option A, the comprehensive assessment was $0.5 + 0.005i$, for B – $0.5 + 0.007i$, for C – $0.5 + 0.092i$, for the "reference" project – $0.5 + 0.008i$. Next, we find the distance between the points – the length of the corresponding vector. Consequently, we can say that the closest to the standard and recommended option is B.

3. Difficulties and issues that need to be refined regarding complex indicators

Using complex numbers, as opposed to real numbers, makes comparisons difficult. We can compare only the real and imaginary parts. To avoid this problem, we suggest developing a "reference" assessment object. That is, a project that will take into account all existing recommendations from the ecological and economic side. When evaluating project options or different projects for the offered indicator, we will compare them with the evaluation of the "reference" object – how far is our indicator from this point.

The offered complex indicator proposed can be used in two directions. The first, when you need to compare different project options of the same territory. The second, when you need to compare (evaluate) different territories. After conducting a spatial and statistical analysis, it is possible to develop "benchmarks" for various natural and agricultural areas. The lands on the territory of Ukraine are located in several natural climatic zones, which are divided into natural and agricultural areas, which differ from each other in relief, natural and climatic conditions, as well as contour and fragmentation. It is precisely because of such significant differences between natural and agricultural areas that it is not desirable to use the same "standard" for comparison. In the calculation of these indicators, with which the existing farms or project options will be compared in the future, it is planned to apply the terrain characteristics. If previously it was difficult to calculate such indicators due to the lack of necessary data and the difficulty of calculation, now using modern geographic information systems and appropriate software (QGIS, ArcGIS, Digitals) it is possible to quickly calculate the above spatial indicators.

A certain obstacle to the calculation and implementation of the above indicators is the lack of information on the characteristics of the communities' territory. Territorial communities have appeared recently and there is no generalized up-to-date and verified information on spatial resources. Information on land resources in full is not yet available. In the direction of overcoming the obstacle, very significant steps are being taken, for example, the use of an information portal, which is constantly filled with information on the land resources use. It should be noted that for a full-scale assessment of the entire territory of Ukraine or even within the boundaries of the natural-agricultural region, there is still not enough information. There is

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a certain positive trend thanks to services (sites) that provide free satellite images of the earth's surface. With the help of GIS programs, you can find information about the physical properties of land plots.

Another obstacle to the use and calculation of complex indicators is the lack of a form of statistical reporting related to the use of land resources. According to the old form, there is data up to 2016. The new form has not been implemented and is at the stage of development, and therefore there is a certain "information vacuum regarding the use of land resources".

Therefore, a promising application of the offered indicator is the monitoring of changes related to the progress and impact of the land reform. For example, after analyzing satellite images of the Earth's surface taken in 2000 and images of 2021, we see that there are two trends. The first trend is an increase in contour and fragmentation without changes in the structure of the land. This is due to the increase in the number of land users and business entities. The second trend is a change in the structure of land, by involving intensive cultivation of fodder land. Both the first and second trends can be calculated and analyzed using the offered indicator. This will make it possible to conduct at least a partial and intermediate assessment of land reform effectiveness. Land relations is a complex multifaceted system and it is difficult to characterize it with one indicator. But there is an opportunity to note trends and evaluate prospects. When spatial planning of the communities' territory, design and planning solutions of larger territorial units (districts, regions of the country) must be taken into account.

The use of complex indicators in land management should help to identify patterns that were not the focus of scientists' attention before. In the future, it is planned to improve the real part of the indicator (the ratio of arable land to the total area). Various multidimensional statistical searches, finding the correlation dependence of environmental effects and economic gains on the value of the above-mentioned indicator will help to do this. But it should be noted that economic calculations are also characterized by a lack of information. There are two levels of problems with statistical data: practical and methodical. The practical one is that costs directly related to production are a trade secret. The methodological level is that the final result of agricultural activity is influenced not only by the production component, but also by others, such as marketing. It is difficult to investigate the direct influence of land, contour, and fragmentation ratio on the economic component of economic activity.

4. Conclusions

The offered evaluation of design and planning solutions index will make it possible to evaluate both the ratio of lands and their spatial placement in an integrated manner. The use of complex numbers will make it possible to implement new analysis approaches in land management to find regularities in the influence of spatial placement on the economic activity results. For territorial communities in Ukraine, an important success factor is the use of arable land, as the most effective agricultural land. Finding a balance between economic benefit and ecological stability is a key task of the territory spatial planning.

The offered approach application requires a significant amount of relevant information. Unfortunately, there are certain obstacles regarding access to the characteristics of the land resources use. Modern software and land remote sensing data allow highly complex analyses. The indicators mentioned above must be tested and improved. Including relief characteristics in complex indicators will provide even more accurate spatial analysis data.

Prospective areas of use of the proposed indicator are the determination of average statistical characteristics of the spatial indicators of the most productive lands. On their basis – determination of optimization parameters, ways of reducing economic costs, achieving ecological balance. First, it is possible to determine the most successful (effective) design and planning solutions. Secondly, there is an opportunity to analyze trends and trends in the development of land relations, to draw conclusions about problems and proposals to overcome them. Territorial communities receive a new decision-making and assessment tool that will allow more efficient use of available land resources. Land management should fully use modern computer technologies, GIS, and mathematical methods. Only multilateral methods of evaluating planning and project decisions will ensure effective spatial development of territorial communities and the country as a whole.

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References

[1] Albrechts L 2004 *Environment and Planning B: Planning and Design* **31**(5) 743–758 URL https://doi.org/10.1068/b3065
[2] Gustafsson S, Hermelin B and Smas L 2019 *Journal of Environmental Planning and Management* **62**(8) 1321–1338 URL https://doi.org/10.1080/09640568.2018.1495620
[3] Rivolin U J 2008 *Planning Practice & Research* **23**(2) 167–186 URL https://doi.org/10.1080/02697450802327081
[4] Sowińska-Świerkosz B and Soszyński D 2022 *Land Use Policy* **119** 106180 ISSN 0264-8377 URL https://doi.org/10.1016/j.landusepol.2022.106180
[5] Sowińska-Świerkosz B and Soszyński D 2019 *Journal of Environmental Management* **248** 109272 ISSN 0301-4797 URL https://doi.org/10.1016/j.jenvman.2019.109272
[6] Nogués S, González-González E and Cordera R 2019 *Journal of Cleaner Production* **225** 510–523 ISSN 0959-6526 URL https://doi.org/10.1016/j.jclepro.2019.03.328
[7] Chang H S, Lin Z H and Hsu Y Y 2021 *Urban Forestry & Urban Greening* **65** 127325 ISSN 1618-8667 URL https://doi.org/10.1016/j.ufug.2021.127325
[8] Oliveira E, Leuthard J and Tobias S 2019 *Land Use Policy* **87** 104031 ISSN 0264-8377 URL https://doi.org/10.1016/j.landusepol.2019.104031
[9] Barneveld R J, van der Zee S E A T M, Greipsland I, Kværnø S H and Stolte J 2019 *Geoderma* **340** 325–336 ISSN 0016-7061 URL https://doi.org/10.1016/j.geoderma.2019.01.017
[10] Drobnik T, Greiner L, Keller A and Grêt-Regamey A 2018 *Ecological Indicators* **94** 151–169 ISSN 1470-160X URL https://doi.org/10.1016/j.ecolind.2018.06.052
[11] Perujo Villanueva M and Colombo S 2017 *Biosystems Engineering* **164** 135–146 ISSN 1537-5110 URL https://doi.org/10.1016/j.biosystemseng.2017.10.003
[12] Janus J and Markuszewska I 2019 *Land Use Policy* **83** 22–31 ISSN 0264-8377 URL https://doi.org/10.1016/j.landusepol.2019.01.024
[13] Janus J and Taszakowski J 2018 *Ecological Indicators* **93** 718–729 ISSN 1470-160X URL https://doi.org/10.1016/j.ecolind.2018.05.050

Biomass potential of forest residues in forests of Ukrainian Carpathians as a component of regional green economy

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Biomass potential of forest residues in forests of Ukrainian Carpathians as a component of regional green economy

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Abstract. The biomass of forest wood residues (waste) in the Ukrainian Carpathians is now an important resource for ensuring energy security under martial law and the formation of strategic directions for energy independence from imported fossil energy resources and the development of a green economy. As a result of the study, the indicators of the total potential of wood biomass of forest wood residues in the forests of the Ukrainian Carpathians were established both in volumetric units and primary energy units. These indicators are differentiated by territorial administrative units of the region and predominant forest stands. The information basis for the assessment of these indicators was the research data on biometric assessment of trees collected in temporary trial plots, as well as mathematical dependencies of conversion factors of biomass components. The study found that the environmentally safe annual potential of the studied resource is about 800 thousand m^3, or 7.7 PJ, which can be additionally involved in the process of generating heat or other types of energy. The results of the study of forest residues biomass potential are an informational component for the formation of a regional program for the development of forest bioenergy in the Carpathian region of Ukraine.

1. Introduction

Use of wood biomass from forest waste is currently not only one of the areas of renewable energy development and a component of green economy mechanisms, but also an important social area for ensuring energy security of Ukraine's population under martial law. An intensive development of the national renewable energy sector is linked, among other things, to the destruction of a significant number of energy infrastructure facilities during missile strikes on the territory of Ukraine. It also stimulates implementation of low-carbon production approaches, as envisaged by the Low-Carbon Development Strategy of Ukraine, and facilitates positive environmental impact in urbanized conditions.

An imbalance of the current paradigm of mankind's energy supply, based on the dominance of fossil fuel energy, is also noted in the Energy Report [1] by World Wildlife Fund (WWF) in cooperation with ECOFYS energy consulting agency. Due to the progressive global decline in reserves of non-renewable natural energy resources (gas, oil, coal) and the urgent need to reduce harmful emissions, the challenge of using alternative fuels has become particularly relevant [2]. Wood biomass from forest waste in forests of Ukrainian Carpathians, one of the most forested regions of the country, serves as an important renewable energy resource for the region's green economy and is an integral part of the national energy sector in the context of energy dependence on fossil energy resources.

The forests in Ukrainian Carpathians, accounting for over a third of Ukraine's wood biomass reserves, remain an important environmental and social factor in development of local communities in mountainous areas. This necessitates the application of environmentally sound approaches to use of forest resources, ensuring a balance between economic, social and environmental components of the regional mountain forest management system.

While focusing on resource potential of forest wood biomass, researchers often do not consider the environmental component of forest stands' functioning, omit the important role of forest residues in logged areas in forming stocks of mineral nutrients as a result of biodegradation [3,4].

Uncontrolled use of wood biomass for energy purposes may have negative consequences for forest plant communities. For example, according to the published research [5], an increase in volume of wood biomass harvesting in Swedish forests may have negative consequences for the environment, forest soil fertility, and conservation of forest biodiversity. Excessive use of logging residues may also have a negative impact on mammal populations [6] and the ability of forest plant communities to provide ecosystem services [7].

The use of wood biomass is characterized by different ways of converting it into heat, electricity, and other types of energy. At the same time, researchers from Latvia [8] prove the inefficiency of using wood biomass for electricity production and conclude that the transition to renewable energy without radical changes in the existing economic system in the country will further exacerbate the environmental problems of bioenergy. When using forest residues for biofuel production, it is also necessary to consider their qualimetric features. A high percentage of bark in forest residues causes the formation of a significant amount of ash in the course of their combustion, which requires an increase in cost of fuel boilers maintenance [9].

The prospects for use of logging residues for energy production were also noted by Spanish and Italian researchers [10], who concluded that use of forest residues from natural forests is more environmentally friendly than wood biomass obtained from energy plantations. Energy from wood biomass can serve as an indicator of energy sustainability in the face of current challenges (extreme weather events, climate change, environmental pollution, loss of biodiversity) [11].

In the process of assessing potential opportunities for involving wood biomass in the energy sector, the long-term planning process is important, given the environmental acceptability, economic feasibility and reliability of resource formation [12]. This approach allows to involve the maximum number of stakeholders for the effective implementation of renewable energy technologies. Given that use of wood biomass as an energy resource ensures the development of low-carbon production, its sustainable use serves as a tool for mitigating global climate change. Thus, according to research by scientists from Thailand [13], if wood biomass is used for bioenergy production in Southeast Asia instead of burning coal, diesel or natural gas, the total emission reduction could be 229.9, 215.4 or 207.9 Tg CO_2 per annuum.

Accumulation of wood biomass in the form of dead wood in forests with a significant anthropogenic load can contribute to an increase in fire hazard due to build-up of forest combustible materials stocks [14, 15]. Therefore, a portion of dead wood can be used as an energy resource without compromising biodiversity conservation.

Thus, based on the analysis of the literature, it can be concluded that forest biomass, including forest residues, remains on the agenda of global scientific community as a strategic renewable energy resource. At the same time, its use should be carried out in compliance with the conceptual framework of sustainable development.

The *purpose* of this research is to assess the potential of biomass of forest residues in forests of Ukrainian Carpathians as an important part of renewable energy resource and a component of regional green economy development.

2. Materials and methods

The research is focused on forest stands in Ukrainian Carpathians, which according to the information from the stand level database run by Industrial Association "Ukrderzhlisproekt" (Ukrainian Industrial Association for Forest Management Planning), cover an area of 2012.3 thousand hectares and feature growing stock of 577.5 million m^3 within four administrative regions (table 1). Spruce, beech, and fir stands predominate in the research region, accounting for about 70 % of forested area. Almost a half of these stands are mid-aged ones.

Table 1. Quantitative characteristics of forest plots in the research region.

Administrative region	Quantity of forest plots, pcs.	Area, thou. ha	Growing stock, Mio. m^3
Zakarpattia	111841	641.9	210.9
Ivano-Frankivsk	132695	531.0	150.4
Lviv	180302	606.6	151.4
Chernivtsi	55463	232.8	64.8
Total	480301	2012.3	577.5

To carry out the research of weight characteristics of biomass components, we used experimental data collected on temporary sample plots using a unified methodology [16]. The total amount of experimental data used for the purposes of our research is 662 model trees, 513 experimental sections of tree trunks and 246 samples of crown branches (table 2).

Table 2. Quantitative characteristics of forest plots in the research region.

Tree species	Quantity, pcs			
	sample trees	sample sections		
		total	including	
			trunk	crown branches
Norway spruce	279	249	150	99
Silver fir	200	342	243	99
European beech	183	168	120	48
Total	662	759	513	246

The research uses the statement that forest wood residues (waste) are primarily represented by wood raw materials harvested in the process of thinning (lighting, clearing and partially first commercial thinning) in the form of whole trees, as well as logging waste, logging residues (parts of trunks, branches, treetops, etc.), stumps and roots that are formed after final cuts, sanitary cuts and other forest tending and care measures.

To establish the total biomass stocks of crown branches, which form the bulk of forest wood residues volume in the forests of Ukrainian Carpathians, we used mathematical dependencies of biomass expansion factors tested for the territory of the research region [17]. To estimate the energy potential of wood biomass of forest residues, we used a dependence that reflects the sum of its structural components and has the following form:

$$PFWW^{tot}_{a,j} = PFP_{a,j} + PFW_{a,j} + PSRA_{a,j}, \tag{1}$$

where $PFWW_a, j$ – total energy potential of forest wood waste in year a over a territory j, m^3; $PFP_t a, j$ – potential of forest products harvested at thinning in young stands (lighting, clearing) in year a over a territory j, m^3; PFW_a, j – potential of forest waste (parts of trunks, branches, treetops, etc.) in year a over a territory j, m^3; $PSRS_a, j$ – potential of stem residues and stumps in year a over a territory j, m^3.

3. Results and discussion

Using information on biometric characteristics of forest stands obtained within the framework of the current State Forest Account and the proposed modeling tools [18], it was found that the total biomass of crown branches in forests of Ukrainian Carpathians exceeds 50.0 million tons of dry matter (table 3). Nearly 45 % of the biomass is accumulated in stands of Zakarpattia region, where its density is 3.8 kg $\cdot$ (m^2)$^{-1}$. This region is dominated by European beech stands (more than 60 % of forested area), which form a much larger crown compared to coniferous tree species. In general, in forests of Ukrainian Carpathians, the share of branches biomass of European beech is 58.2 %.

Table 3. Biomass of crown branches in forests of Ukrainian Carpathians.

Administrative region	Biomass of crown branches, million ton						Mean, kg $\cdot$ (m^2)$^{-1}$
	total	by tree species: Norway spruce	Silver fir	European beech	other species		
Zakarpattia	24.5	2,7	0.2	19.6	2.0		3.82
Ivano-Frankivsk	12.0	4.4	0.6	4.9	2.1		2.25
Lviv	12.5	1.4	1.0	4.8	5.4		2.06
Chernivtsi	5.8	1.2	0.6	2.6	1.4		2.47
Total	54.8	9.7	2.4	31.9	10.8		2.72

Every year, more than 2.5 million m^3 of wood is harvested in the research region. As a result, a significant amount of forest wood residues is formed. They can serve as a significant source of energy resource that must be used in compliance with an ecologically balanced approach to nutrients cycling in forest plant communities while ensuring low fire hazard.

To assess the potential of wood biomass in forest residues in units of primary energy (Joules), quantitative values of energy content per unit volume (table 4) were established based on density of biomass components [18]. The energy value of biomass was determined based on data by Shvidenko et al [17]. In terms of energy value, 1 m^3 of wood over bark of European beech branches is equivalent to 310 m^3 of natural gas. In the research region, beech biomass has the highest consumer demand as an energy resource for heat production during the heating season.

A 110-120 years aged beech stand features the proportion of crown branches of about 20-25 % of its total stem stock. For spruce and fir, this figure is about 10-15 %. Currently, more than 80 % of logging residues remain on site after logging, some of them can be used for heat production without harming the environment.

The research resulted in an assessment of environmentally safe potential of wood biomass from forest wood residues. This type of energy potential accounts for requirements related to

Table 4. Energy value of tree biomass components (crown branches).

Tree species	Energy value of dry matter of live biomass components of crowns, GJ $\cdot$ $(m^3)^{-1}$		
	wood	bark	wood over bark
Norway spruce	9.959	7.653	9.351
Silver fir	9.476	8.511	9.083
European beech	10.156	8.547	9.852

biological cycling of nutrients, biodiversity conservation, and compliance with environmental requirements for use of forest wood waste. It also takes into account orographic features of mountain forests. In total, more than 800 thousand m^3 (table 5) of forest residues can be additionally used as a renewable energy resource annually.

Table 5. Biomass potential of forest residues in forests of Ukrainian Carpathians.

Administrative region	Biomass of forest wood residues, thou. m^3				
	total	by tree species			
		Norway spruce	Silver fir	European beech	other species
Zakarpattia	239.7	26.6	2.0	191.3	19.8
Ivano-Frankivsk	171.8	63.2	8.1	70.8	29.7
Lviv	206.2	22.7	16.1	78.9	88.6
Chernivtsi	182.7	37.1	19.3	83.3	43.1
Total	800.4	149.5	45.5	424.3	181.1

The energy value of the studied biomass potential of forest residues in forests of Ukrainian Carpathians is almost 7.7 PJ (table 6), which is roughly equivalent to more than 240 million m^3 of natural gas.

Table 6. Energy potential of forest wood residues biomass in the forests of the region.

Administrative region	Energy potential of forest wood residues biomass, TJ				
	total	by tree species			
		Norway spruce	Silver fir	European beech	other species
Zakarpattia	2338.1	248.7	18,4	1884.7	186.3
Ivano-Frankivsk	1641.9	590.5	73.8	697.8	279.7
Lviv	1969.5	211.8	146.0	777.3	834.3
Chernivtsi	1748.0	346.7	174.9	820.5	405.9
Total	7697.4	1397.8	413.1	4180.3	1706.3

At the same time, the main problem of utilizing the assessed energy potential is the logistics of this resource to the end user. At present, one of the problems hindering the introduction of new technologies for energy use of wood in the Carpathian region of Ukraine is the lack of a developed network of high-quality forest roads. Here, 10 to 20 % of forest areas covered with forest vegetation remain technically inaccessible. An important precondition for efficient production of solid biofuels is creation of a closed technological cycle of wood processing, starting with logging and ending with processing of waste into pellets or other types of biofuels. The production process should start at a forest plot and a forest road. It should include all logistics and other stages that would guarantee high economic efficiency, low production costs and, ultimately, high price competitiveness compared to traditional energy resources. The system of financial and economic incentives for development of forest bioenergy in the region also needs to be optimized. Due to the lack of financial incentives for implementation of bioenergy projects from the state and local governments in the region, most of them are implemented with the support of foreign funds and programs.

4. Conclusions

The research results present quantitative values of biomass potential of forest wood residues in forests of Ukrainian Carpathians, which will serve as an information basis for formation of a strategy for development of regional forest bioenergy and green economy. In general, the total biomass of crown branches, as the main component of forest wood residues, is more than 50.0 million tons of dry matter. Almost half of this volume is accumulated in the stands of Zakarpattia region. The energy value of the biomass resource varies from 9.083 GJ $\cdot$ $(m^3)^{-1}$ for Silver fir stands to 9.852 GJ $\cdot$ $(m^3)^{-1}$ for European beech stands. In terms of energy value, 1 m^3 of wood over bark of European beech branches is equivalent to approximately 310 m^3 of natural gas. Currently, more than 80 % of logging residues are left for biodegradation at logging sites. According to the results of our research, more than 800 thousand m^3 of forest wood residues can be additionally used as a renewable energy resource without harming the environment and functioning of forest plant communities in the region. In energy terms, this is almost 7.7 PJ, or approximately more than 240 million m^3 of natural gas. At the same time, to facilitate the efficient use of this resource, it is necessary to ensure compliance with the basic principles of sustainable development of the mountainous region, balancing its economic, environmental and social aspects. State regulation, regulatory support, financial and economic incentives for development of forest bioenergy are necessary in the region. Also, development of wood biomass processing technologies as well as development of regulatory and information tools for assessing and monitoring energy potential of forest biomass are of crucial importance. Implementation of the above framework recommendations will facilitate implementation of positive systematic changes in the renewable energy sector, enable accounting for energy needs of the society and uphold energy security principles during martial law.

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References

[1] Ram M, Bogdanov D, Aghahosseini A, Gulagi A, Oyewo A S, Child M, Caldera U, Sadovskaia K, Farfan J, Barbosa L S N S, Fasihi M, Khalili S, Dalheimer B, Gruber G, Traber T, De Caluwe F, Fell H J and Breyer C 2019 Global Energy System Based on 100 % Renewable Energy – Power, Heat, Transport and Desalination Sectors Lappeenranta University of Technology Research Reports 91 Lappeenranta University of Technology and Energy Watch Group Lappeenranta, Berlin URL http://energywatchgroup.org/wp-content/uploads/EWG_LUT_100RE_All_Sectors_Global_Report_2019.pdf

[2] Geletukha G and Zheliezna T 2021 *Ecological Engineering & Environmental Technology* **22**(5) 73–81 ISSN 2719-7050 URL https://doi.org/10.12912/27197050/139346
[3] Geletukha G, Zheliezna T, Pastukh A and Drahniev S 2018 *Possibilities for harvesting wood fuel in Ukraine's forests* (BAU)
[4] Prokip A 2011 *Securing energy safety: past, present and future* (Lviv: EUCC)
[5] de Jong J, Akselsson C, Egnell G, Löfgren S and Olsson B A 2017 *Forest Ecology and Management* **383** 3–16 ISSN 0378-1127 Sustainability of increased forest biomass harvest from a Swedish perspective URL https://doi.org/10.1016/j.foreco.2016.06.028
[6] Ranius T, Hämäläinen A, Egnell G, Olsson B, Eklöf K, Stendahl J, Rudolphi J, Sténs A and Felton A 2018 *Journal of Environmental Management* **209** 409–425 ISSN 0301-4797 URL https://doi.org/10.1016/j.jenvman.2017.12.048
[7] Eggers J, Melin Y, Lundström J, Bergström D and Öhman K 2020 *Sustainability* **12**(10) 4089 ISSN 2071-1050 URL https://doi.org/10.3390/su12104089
[8] Abolins J and Gravitis J 2015 Limits to Sustainable Use of Wood Biomass *Sustainable Development, Knowledge Society and Smart Future Manufacturing Technologies* ed Leal Filho W, Úbelis A and Bērziņa D (Cham: Springer International Publishing) pp 199–206 ISBN 978-3-319-14883-0 URL https://doi.org/10.1007/978-3-319-14883-0_13
[9] Nosek R, Holubcik M and Jandacka J 2016 *Bioresources* **11**(1) 44–53 URL https://doi.org/10.15376/biores.11.1.44-53
[10] González-García S and Bacenetti J 2019 *Science of The Total Environment* **647** 158–168 ISSN 0048-9697 URL https://doi.org/10.1016/j.scitotenv.2018.07.295
[11] Majchrzak M, Szczypa P and Adamowicz K 2022 *Energies* **15**(15) 5381 ISSN 1996-1073 URL https://doi.org/10.3390/en15155381
[12] Vukasinovic V, Gordic D, Zivkovic M, Koncalovic D and Zivkovic D 2019 *Energy* **175** 818–829 ISSN 0360-5442 URL https://doi.org/10.1016/j.energy.2019.03.105
[13] Sasaki N 2021 *Resources, Conservation and Recycling* **173** 105737 ISSN 0921-3449 URL https://doi.org/10.1016/j.resconrec.2021.105737
[14] Gumeniuk V, Holiaka D, Soshenskiy O and Koren V 2021 *Forestry Ideas* **27**(1) 3–18 URL https://forestry-ideas.info/issues/issues_Download.php?download=389
[15] Bilous A, Matsala M, Radchenko V, Matiashuk R, Boyko S and Bilous S 2019 *Forestry Ideas* **25**(1) 196–219 URL https://forestry-ideas.info/issues/issues_Download.php?download=327
[16] Lakyda P 2002 *Live biomass of Ukraine's forests* (Ternopil: Zbruch)
[17] Shvidenko A, Nilsson S and Obersteiner M 2004 Wood for bioenergy in Russia: Potential and Reality *Wood Energy in the Industrialized World. Proceedings of the International BIOCLIMECO Workshop; Graz, Austria, 19-20 November 1999* ed Kohlmaier G H (Frankfurt, Germany: ZUF-Verlag) pp 323–340
[18] Vasylyshyn R 2018 *Environmental and energy potential of forests in Ukrainian Carpathians and its sustainable use* (Kyiv: LLC Komprint)

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Cadastral and landscape modeling of lakes as a prerequisite for protected and recreational nature resource management

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Abstract. The cadastral information about the lakes of the nature reserve fund (NRF) should be based on landscape-geographic principles using modern geo-information systems.Within the research, based on the instrumental field research and the use of software packages ArcGIS Desktop and ReefMaster Software, a bathymetric map of Lake Serednie (Nobel National Natural Park, Ukraine) and other spatial models were developed. The main hydrological and morphometric parameters of the lake basin were calculated, a landscape map of the natural aquatic complex was created and its landscape metric analysis was carried out at the level of aquatic tracts and facies. The research revealed changes in the level regime and shoreline of the lake caused by the long dry periods of 2016-2021 and life activity of beavers. The created integrated cadastral landscape model of the lake with limnology parameters should serve as a basis for the recreational nature use, monitoring and geo-ecological certification of the reservoirs of the NRF.

1. Introduction

According to Article 56 of the Law of Ukraine "On the Nature Reserve Fund of Ukraine", the state cadastre of the territories and objects of the nature reserve fund (NRF) is a system of necessary and reliable information about the natural, scientific, legal and other characteristics of the territories of the objects included to the NRF [1]. In Ukraine, the natural reserve fund is safeguarded as a national asset and subject to a distinct set of rules for its protection, reproduction, and usage. Furthermore, Ukraine regards this fund as a crucial component of the global network of special-protected natural territories and objects. The corresponding cadastral system should incorporate current geospatial data, metadata, and various online sources, including publications, that comply with the terms of the Spatial Data Infrastructure [2]. In 2021, the Ministry of Environmental Protection and Natural Resources of Ukraine presented an electronic cadastre of territories and objects of the NRF. The information layer "Nature Reserve Fund" appeared on the Public Cadastral Map, which at that time contained information on 8,633 NRF objects, or 88 percent of the area of the NRF of Ukraine [3].

Lake reservoirs occupy a prominent place in the structure of the NRF objects of Ukraine. They are part of nature reserves, national nature parks, regional landscape parks, landscape reserves, hydrological natural monuments, protected tracts, etc. Unfortunately, there is rather limited information about lakes of the NRF and, it should be noted, such situation is not unique [4]. On the Public Cadastral Map, lake objects of the NRF and other water bodies are shown as separate entities with provided information about the area, ownership, etc. Undoubtedly, information on some parameters of land use and landscape components can be added in other layers.

Today, one of the important tasks of protected nature resource management is the creation of an information database about local NRF objects, including lakes, which should later appear on the Internet portals of the institutions of the nature reserve fund. The cadastral information should serve as a basis for recreational nature use, monitoring observations, geo-ecological certification of water bodies [5]. In 2015, Svidzynska et al updated the issue of developing an open cadastre of protected areas of Ukraine [6], which support geo-ecological approaches in the organization of nature reserves.

Among the other studies, which are similar in subject matter, it is worth highlighting the work on the anthropogenic loads on surface water status in Lithuania [7]. A model of geographic management of a nature reserve [8] was developed within the framework of the "Electronic Turkey" project.

Some studies were devoted to the validation of remote sensing indices for water monitoring using Sentinel-2 [9, 10], which can be applied to the cadastre development of lake systems of protected areas. Although successfully tested the methods of capturing littoral zones (up to 1.6 m under clear water conditions) using a UAV complex with a LIDAR scanner on board [11]. The use of the proposed technology greatly facilitates the collection of data for cadastral landscape modeling of lakes, since the shallow zone with higher aquatic vegetation is the most inconvenient for measurements.

For a long time, we have been conducting landscape and limnology studies within the boundaries of Polissia region of Ukraine with the aim of developing cadastral and landscape models of lakes [12, 13], primarily in the territory of the NRF.

2. Materials and methodology

The model protected nature area of this research is Nobel National Natural Park (NNP) in Ukraine, which is located within the physiographic region of Volyn Polissia. The landscapes of the park are characterized by an extensive hydrographic network, swampy wetland complexes, sand dunes and green massifs of forests with areas of cranberries, blueberries, lingonberries, etc. The park includes 12 lakes (Nobel, Omyt, Nihovyshche, Zasvitske, Postvitske, Zadovzhe, Ostrivske, Velyke, Serednie, Khoromne, Lypenske, Liubynske).

The lakes play a significant role in the hydrological functioning of the landscape, the accumulation of fresh water and organic-mineral resources represented by sapropel. Among the most important functions – serving as habitats for waterfowl and numerous migratory bird species. The lakes of Nobel NNP have significant recreational and tourist potential. Among the lakes of the park, a group of Ostrivski lakes stands out. This group includes a picturesque Lake Serednie, which was formed in the Nyzhnostyrskyi physical-geographical district of Volyn Polissia (figure 1).

The development of the cadastral landscape model of Lake Serednie (North 51.72392176915384, East 25.834182861365576) included field instrumental research, in particular, high-precision echo sounding of the reservoir, research into the composition and thickness of lake sediments, the study of the species diversity of above-water and underwater plant communities, and determination of the temperature regime in the summer. The hydrometric work was carried out in May 2021 using a Humminbird 597ci HD sounder mounted on the transom of a rubber boat. The water level during the measurements was recorded using a Leica GNSS/RTK receiver. SRTM v.3 radar survey data were processed in the ArcGIS Desktop software complex to set the boundaries and configuration of the catchment area. Probing of the bottom sediments of the lake was carried

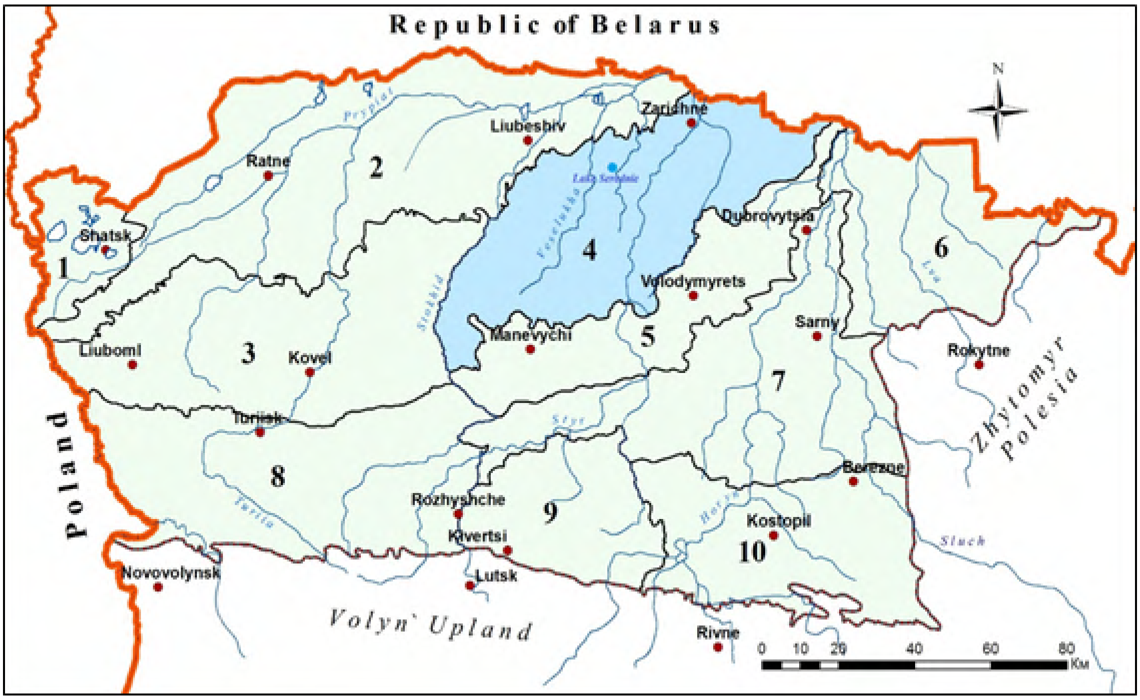


Figure 1. Localization of the Lake Serednie basin on the scheme of physical and geographical zoning of Volyn Polissia. *Physiographic regions:* 1 – Shatsk, 2 – Upper-Prypiat, 3 – Liuboml-Kovel, 4 – Nyzhnostyrskyi, 5 – Manevychi-Volodymyrets, 6 – Lva-Horyn, 7 – Kolky-Sarny, 8 – Turiisk-Rozhyshche, 9 – Kivertsi-Tsuman, 10 – Kostopil-Berezne.

out from the ice in winter with a spoon-type geological drill.

The next stage was the processing of field materials, development of a bathymetric map and landscape mapping of Lake Serednie. The cartographic models were developed using ArcGIS Desktop and ReefMaster Software. From the landscape point of view, we consider the lake to be a natural aquatic complex (NAC) of the rank of a complex tract. The landscape map of the NAC of the lake was developed based on the materials of the bathymetric survey, taking into account the micro-relief of the lake basin, the composition and thickness of sapropel deposits, the species diversity of the plant communities of the reservoir and thermal features.

The research methodology was based on the studies on the field geographical research [14], underwater landscape science [15], limnology [16], bathymetry and GIS mapping [17,18], as well as many years of experience in constructive landscape modeling of lake-basin systems in Polissia region of Ukraine.

The purpose of the research is to develop a cadastral landscape model of Lake Serednie (Nobel NNP) for the needs of protected and recreational nature resource management.

3. Results and discussion

The basin of Lake Serednie was formed in the following landscape areas: 1) high areas between rivers on water-glacial sands with close deposits of chalk marls; 2) inter-fluvial marshy plains on fluvial-glacial and ancient alluvial deposits. The Pleistocene glaciation, as well as postglacial processes, had a significant impact on the formation and development of the landscapes of the basin system of Lake Serednie and Nobel NNP as a whole. The activity of water flows, aeolian processes and excessive moistening subsequently affected the morphological structure of the landscapes of Nobel NNP and lake-basin systems (LBS).

The field research in the lake basin and its adjacent territories revealed dominant morphological units of the landscape of a lower rank, in particular, tracts (or geotopes):

1) Hills and dunes with gentle (6-10°) slopes, covered with lichen-shrub pine forests on hidden podzolic, sometimes crushed stone, sandy soils.
2) Elevated areas between rivers, complicated by karst funnels, covered with lichen-bilberry-green moss pine and birch-pine forests on slightly podzolic, sometimes clayey, sandy soils.
3) Undulating areas between rivers covered with sedge-bilberry-green moss and various grass-green moss oak-pine and birch-oak-pine forests on sod-weak podzolic clayey sandy and loamy soils, sometimes meliorated.
4) Local closed mounded depressions covered with various grass-cereal-green moss and sedge-juncus -green moss alder-birch-pine sparse forests on sod gumbo sandy and sandy loamy soils.
5) The lakeside narrow depressions, which are filled with water during floods, covered with reed-sedge-herbaceous and shrubby-sedge-reed alder and willow small forests on meadow layered gumbo sandy and sandy loamy soils.
6) Lake depressions of irregular shape formed on sapropel deposits.

The catchment area of Lake Serednie is not big and makes 54.3 hectares. It is elongated in a sub-latitudinal plan from the northwest to the southeast in accordance with the configuration of the lake.

Based on the results of echo sounding data processing, we built a bathymetric map of Lake Serednie (figure 2).

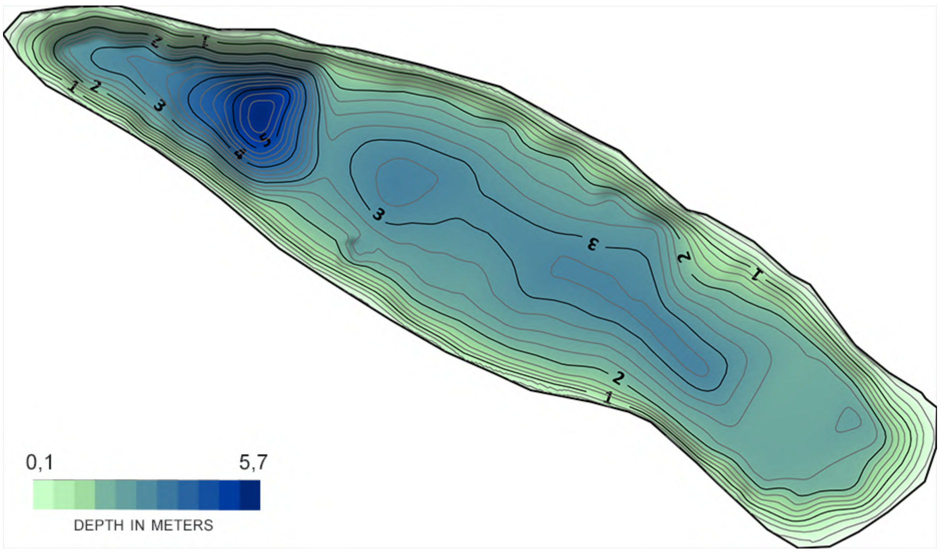


Figure 2. Bathymetric map of the Lake Serednie.

Isobaths are drawn at intervals of 0.25 m. Up to 2.0 m, the depth increases gradually, and from 2.0 m, the isobaths have some differences. In the northwestern part, a funnel-shaped depression with a maximum depth of 5.67 m was found from 4.0 m and deeper. The central part of the bed of the lake basin has a depression of elongated shape of more than 3.0 m. The average depth of the reservoir is 2.4 m. The area of the lake is 0.19 km^2. The length of the reservoir is 1.002 km, the maximum width is 0.262 km, and the average is 0.190 km. The coastline has a length of 2.257 km. The northwestern part of the coastline and lakeside terrace is undergoing

Table 1. Morphometric and hydrological characteristics of the Lake Serednie*.

F, ha	$H_{abs.}$, m	$h_{mid.}$, m	$h_{max.}$, m	L, km	$W_{max.}$, km	$W_{mid.}$, km	l, km	Ct.	$C_{len.}$
0.1948	145.6	2.4	5.67	1.002	0.262	0.190	2.257	0.824	5.274
$C_{cap.}$	$C_{op.}$	$C_{dep.}$	$V_{lake.}$, $m^3 \cdot 10^3$	A	Δ S, km^2	W^{**}_{influx}., $m^3 \cdot 10^3$	$a_{wat.}$	Δ $a_{wat.}$, mm	A_{layer}, mm
0.471	0.079	4.174	435.2	0.264	3.789	68.5	0.157	6.353	801.5

* Table notation: F – area; $H_{abs.}$ – absolute height of the water level; $h_{max.}$ – maximum depth; $h_{mid.}$ – average depth; L – Length; $W_{max.}$ – maximum width; l – length of the shoreline; $C_{t.}$ – coefficient of shoreline unevenness ; $C_{len.}$ – coefficient of the lake lengthening ; $C_{cap.}$ – coefficient of capacity; $C_{op.}$ – coefficient of openness; $C_{dep.}$ – coefficient of depth; V_{lake} – lake volume; A – area index; ΔS – specific catchment; W_{influx} – volume of inflow water from the catchment; $a_{wat.}$ – conditional water exchange; $\Delta a_{wat.}$ – specific water exchange; A_{layer} – water storage level on the catchment surface.
** The average annual runoff module is 4.0 $dm^3/s{\cdot}km^2$.

transformations due to the life activity of beavers (numerous burrows leading from the shore into the lake, fallen trees). The volume of the lake water is 435.2 thousand m^3. Other morphometric and hydrological parameters of the lake are given in table 1.

The developed three-dimensional model of Lake Serednie is an additional element of the visualization of the lake basin micro-relief (figure 3a).

It clearly shows a depression in the cone-shaped northwestern part of the basin bed. The aforementioned funnel-shaped depression is very well shown on the longitudinal profile of the underwater topography of the lake (figure 3b). The slopes of the lake basin from the water surface are steep (10-15°) up to 2.0 m, very steep (15-20°) up to 3.0 m, and steep (more than 20°) from 3.0 m and deeper. The differentiation of the relief of the basin by the steepness of the slopes is important in the further development of the legend of the landscape map, in particular, the determination of the processes of accumulation or transit of mineral particles and dead remains of aquatic organisms.

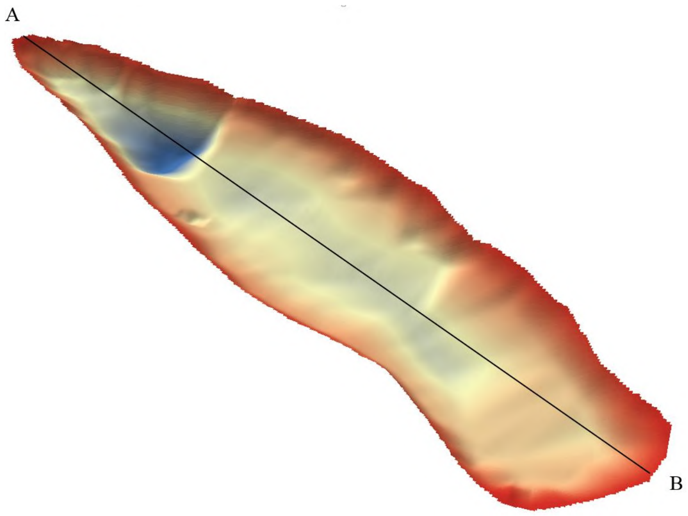
The relief of the lake basin affects the distribution of areas and volumes of water masses of the lake (figure 4).

The area of the littoral zone of the reservoir with a depth of up to 3.0 m is the largest and is 15.35 hectares (78.8 %), it accumulates 413.3 thousand m^3 of water masses (94.95 %). 21.20 % of the area of the lake with 20.9 thousand m^3 of water is at a depth of more than 3.0 m.

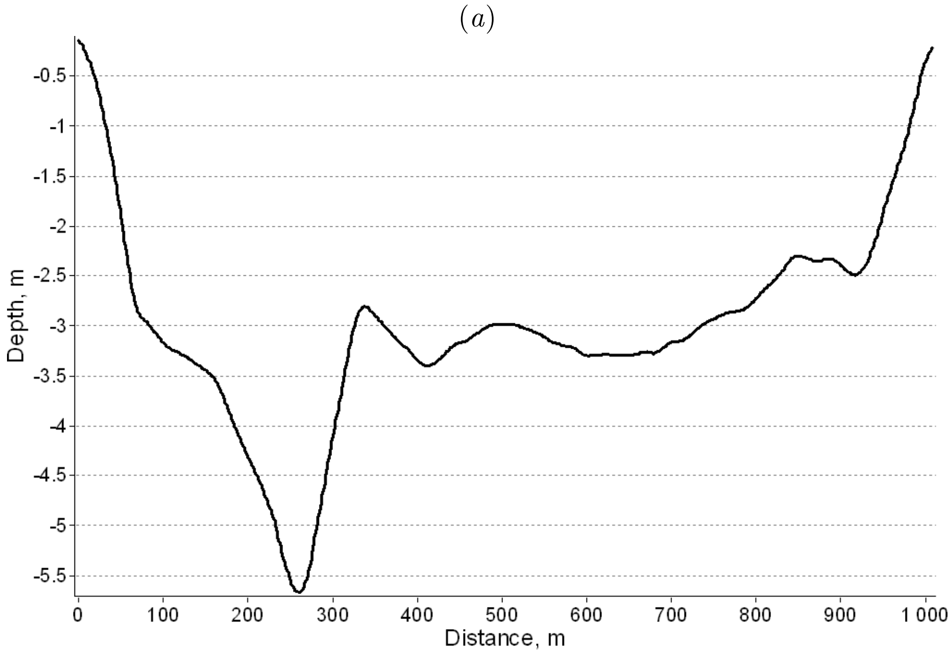
Based on the results of bathymetric surveying, landscape field research and computer processing of materials, a digital landscape map of Lake Serednie was developed (figure 5).

Typical landscape elements shown in figure 5:

I. *Littoral aqua subtract on sandy-muddy, peat-swamp sediments and sapropel underlain by alluvial sands with species diversity of surface and underwater plant communities.*
   Aquafacies:
   1.1. Littoral, accumulative peat-swamp and sandy-muddy of low-thickness (up to 0.5 m) Carex-Typha-Phragmites associations, with a homogeneous temperature regime in summer.
   1.2. Littoral, accumulative swamps and peat-swamps of low-thickness (up to 1.5 m) sparse



(a)



(b)

Figure 3. Three-dimensional visualization (a) and long axis profile A-B (b) of the Lake Serednie.

higher aquatic plants, with a homogeneous temperature regime in summer.

1.3. Littoral, abrasion-accumulative sandy-muddy of low-thickness (0.5-1.0 m) sparse Potamogeton associations, with homogeneous temperature regime in summer, complicated by fallen trees and beaver activity.

1.4. Littoral, abrasion-accumulative muddy-sandy and sandy of low-thickness (0.5-1.0 m), with impoverished underwater vegetation and a homogeneous temperature regime in summer.

1.5. Littoral, accumulative-transit algal-carbonate-sapropel of low-thickness (1.0-2.50 m) filamentous-chara algae associations, with a homogeneous temperature regime in summer.

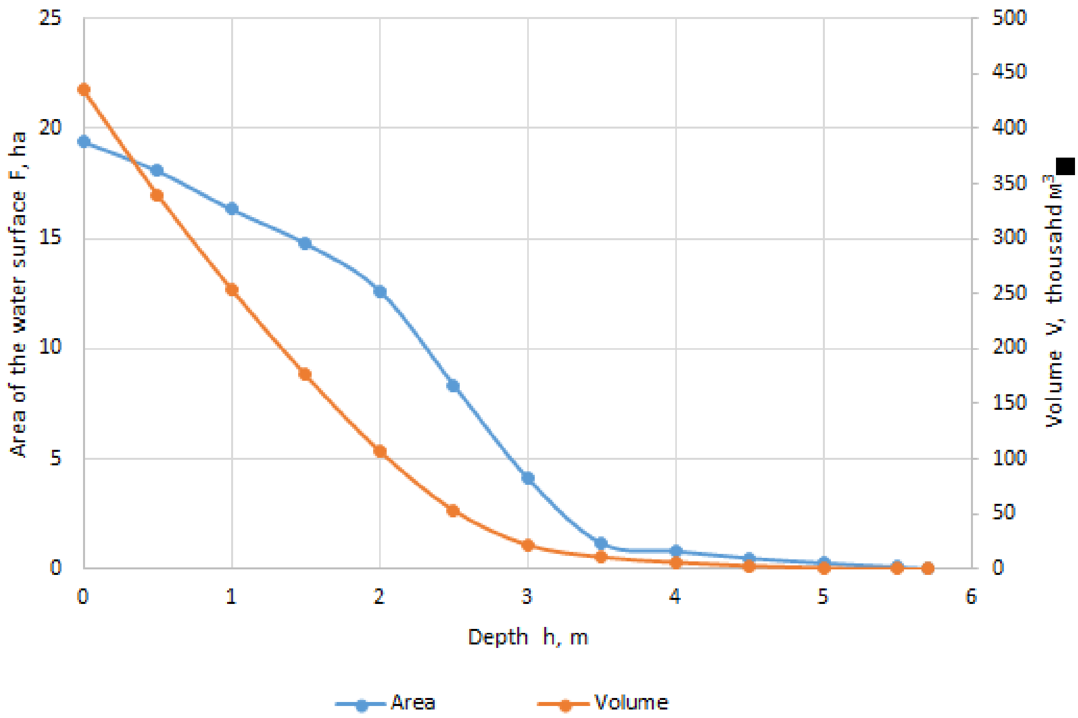


Figure 4. Morphometric curves of areas and volumes of water of the Lake Serednie.

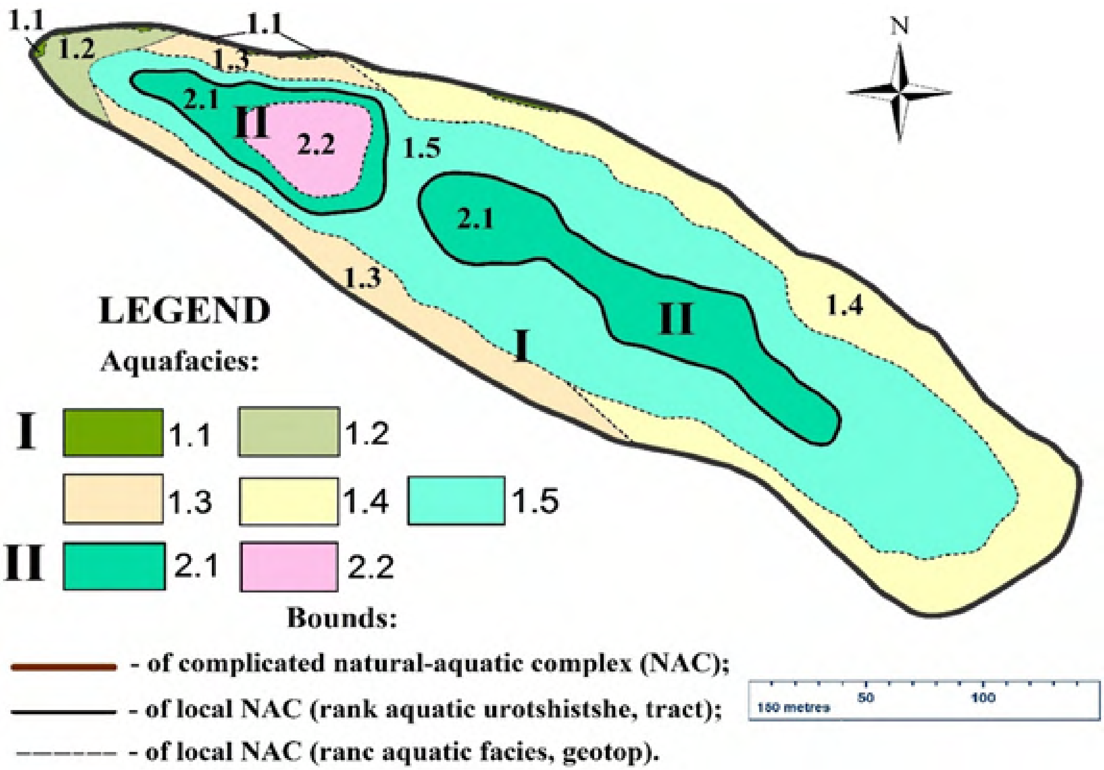


Figure 5. Landscape structure of the natural-aqual complex of Lake Serednie.

II. *Sublittoral-profundal aqua subtract on clay-limestone and organic-limestone sapropel underlain by carbonate loams, with impoverished species diversity of underwater vegetation.* Aquafacies:
   2.1. Sublittoral, accumulative and transit-accumulative clay-limestone-sapropel of medium-thickness (2.5-3.0 m) free-floating algae, with a heterogeneous temperature regime in summer.
   2.2. Profundal, accumulative funnel-shaped depressions organic-limestone-sapropel of medium-thickness (3.0-3.5 m) single floating algae, with a slight temperature amplitude in summer.

Two types of aquafacies were identified in the sublittoral-profundal aqua subtract with depths of more than 3.0 m. In total, there are 13 landscape contours in the NAC; the average area of a landscape contour is 1.5 hectares. Other landscape metric characteristics of Lake Serednie NAC are given in table 2.

Table 2. The complexity of the natural-aqual complex territorial structure of the Lake Serednie.

NAC type		Area of NAC type, ha		% of the type area	
Subtract	Aquafacies	Subtract	Aquafacies	Subtract	Aquafacies
I.		15.35		78.80	
	1.1		0.14		0.71
	1.2		0.42		2.16
	1.3		1.88		9.65
	1.4		4.40		22.59
	1.5		8.51		43.69
II.		4.13		21.20	
	2.1		3.35		17.20
	2.2		0.78		4.0
Totally		19.48	19.48	100.0	100.0

The research identified two aqua subtracts and seven types of aquafacies in the lake NAC. The littoral aqua subtract with depths mainly up to 3.0 m occupies more than 78.0 % of the NAC area and includes five types of aquafacies. The differentiation of aquafacies was carried out taking into account the micro-relief of the lake, the composition and thickness of bottom sediments, the characteristics of aquatic plant communities and the temperature regime in the summer season.

4. Conclusion

The research established that during the summer seasons of 2016-2021, the water level in the lake changed a lot. The retreat of the water cut from the shoreline of the lake was 5.0-6.5 m in the southeastern part of the reservoir. The shoreline of the lake undergoes noticeable changes due to the life activity of beavers, especially the littoral aquafacies with index 1.3. In our opinion, the activity of beavers affected the impoverished state of surface and underwater plant communities. The railway embankment is a limiting factor in the inflow of surface water from the catchment area in the northwestern sector.

The developed series of cartographic models:

1. Reflects the current geoecological state of Lake Serednie and is important in evaluating the geoecological parameters of the whole lake landscape system and its individual elements, and in revealing its functional features.
2. Acts as an information and analytical basis for planning measures to optimize nature use and protect water resources from pollution and quality impairment. The spatial models and typological structure of the land areas within the lake basin and the aquatic complex are especially important in this respect.

The bathymetric maps, the calculated main hydrological parameters of the lake, and the developed aquatic complex model should become the basis of the landscape and cadastral passport of Lake Serednie for the needs of protected and recreational nature resource management.

The benchmark landscape and limnology characteristics of the entire lake basin should become the starting point of further monitoring observations.

In the conditions of climate change and its regional components, the demand for such research will only grow.

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References

[1] Verkhovna Rada of Ukraine 1992 On Nature Reserve Fund of Ukraine URL `https://zakon.rada.gov.ua/laws/card/2456-12`
[2] Ogryzek M, Tarantino E and Rzasa K 2020 *ISPRS International Journal of Geo-Information* **9**(12) 755 ISSN 2220-9964 URL `https://doi.org/10.3390/ijgi9120755`
[3] HO "Zelenyi lyst" 2021 Vidkrytyi elektronnyi kadastr zapovidnykiv i pryrodnykh parkiv ziavyvsia v Ukraini [An open electronic cadastre of nature reserves and natural parks has appeared in Ukraine] URL `https://zeleniy-list.od.ua/kadastr/`
[4] Argillier C, Carriere A, Wynne C, Hellsten S, Vartia K and Poikane S 2023 *Science of The Total Environment* **855** 158781 URL `https://doi.org/10.1016/j.scitotenv.2022.158781`
[5] Afanasyev S O 2019 *Hydrobiological Journal* **55**(2) 3–17 ISSN 0018-8166 URL `https://doi.org/10.1615/HydrobJ.v55.i2.10`
[6] Svidzinska D, Vasyliuk O, Seliverstov O, Shyriaieva D, Biatov A, Diadin D, Ponomarova A, Sklyar O, Vynokurova S, Luchnykova I and Kleshnin A 2015 Development of the open cadastre of protected areas in ukraine *Geomatics Workbooks n° 12 – "FOSS4G Europe Como 2015"* pp 225–231 URL `https://www.researchgate.net/publication/313386226`
[7] Česonienė L, Šileikienė D, Marozas V and Čiteikė L 2021 *Sustainability* **13**(8) 4341 ISSN 2071-1050 URL `https://doi.org/10.3390/su13084341`
[8] Çoruhlu Y E and Çelik M Ö 2022 *Land Use Policy* **122** 106357 ISSN 0264-8377 URL `https://doi.org/10.1016/j.landusepol.2022.106357`
[9] Ciężkowski W, Frąk M, Kardel I, Kościelny M and Chormański J 2023 *Scientific Review Engineering and Environmental Sciences (SREES)* **31**(4) 283–293 URL `https://doi.org/10.22630/srees.4482`
[10] Giuliani C, Veisz A C, Piccinno M and Recanatesi F 2019 *European Journal of Remote Sensing* **52**(sup4) 64–73 URL `https://doi.org/10.1080/22797254.2019.1689796`
[11] Chormański J, Nowicka B, Wieckowski A, Ciupak M, Jóźwiak J and Figura T 2021 *Remote Sensing* **13**(9) 1833 ISSN 2072-4292 URL `https://doi.org/10.3390/rs13091833`
[12] Kovalchuk I P, Martyniuk V O and Šeirienė V 2020 *Visnyk of V. N. Karazin Kharkiv National University, series "Geology. Geography. Ecology"* (53) 239–254 URL `https://doi.org/10.26565/2410-7360-2020-53-18`
[13] Martyniuk V, Korbutiak V, Hopchak I, Kovalchuk I and Zubkovych I 2023 *Baltica* **36**(1) 13–29 URL `https://doi.org/10.5200/baltica.2023.1.2`
[14] Herenchuk K I, Rakovska E M and Topchiiev O G 1975 *Field geographical researches* (Kyiv: Vyshcha shkola)

[15] Petrov K M 1989 *Podvodnye landshafty: teoriia, metody, issledovaniia [Subaqueous Landscapes: Theory, Methods, Investigation Methods]* (Leningrad: Nauka) ISBN 9785020266148 URL `https://books.google.com.ua/books?id=EFk4AAAAIAAJ`
[16] Wetzel R G 2001 *Limnology* 3rd ed (Academic Press) URL `https://doi.org/10.1016/C2009-0-02112-6`
[17] Hamilton S E, McGehee D D, Nyamweya C, Ongore C, Makori A, Mangeni-Sande R, Kagoya E, Kashindye B B, Elison M, Shaban S S, Mlaponi E, Mwainge V M, Ocaya H, Krach N, Ogari Z, Mugeni B, Taabu-Munyaho A, Kayanda R, Muhumuza E and Natugonza V 2022 *Scientific Data* **9**(1) 642 ISSN 2052-4463 URL `https://doi.org/10.1038/s41597-022-01742-3`
[18] Gergel S E and Turner M G 2017 *Learning Landscape Ecology: A Practical Guide to Conceptsand Techniques* 2nd ed (New York, NY: Elsevier) URL `https://doi.org/10.1007/978-1-4939-6374-4`

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Social and environmental features in domestic and international minerals resources classification systems

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Social and environmental features in domestic and international minerals resources classification systems

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Abstract. This paper is aimed at a comparison of Ukrainian and international resource classification systems' fundamental features. As a result, the most common and different features were outlined. The importance of accounting for the social and environmental viability of projects is determined. This study highlights the significance of the harmonization of domestic classification with international standards.

1. Introduction

All known international standards for the assessment of reserves and resources, as well as domestic regulatory documents, contain object classifications according to important geological and industrial features. These systematizations don‘t appear by chance, and as a rule, reflect the traditions and stages of exploration and evaluation of mineral deposits in a particular region.

The classification of mineral reserves and resources of the State Subsoil Fund establishes the principles for calculating, geological and economic assessment and state accounting of mineral reserves that are common for the State Subsoil Fund of Ukraine according to the level of their industrial significance and the degree of geological and feasibility study, the conditions that determine the readiness of explored mineral deposits for industrial development, as well as the basic principles for quantifying mineral resources [1]. The practice of using this classification systematizes mineral reserves and resources according to certain levels of industrial significance and the degree of technical, economic, and geological study. This classification contains distributable classes that are identified using an international three-order numeric code. Today our classification is harmonized with the United Nations Framework Classification for Resources (UNFC) 2009 version despite the fact that there is already an updated version of 2019 [2].

The relevance of this study is related to the integration of domestic subsoil use into European industries, as well as into the global systems for investing in mining facilities. Thus, the domestic mineral resource base takes into account many minerals from the list of critical and strategic ones for such countries as the United States of America, Canada, Japan, Australia, and the European Union. Understanding the availability and maturity of our deposits will accelerate their investment and development. Understanding the requirements of international standards for the exploration of deposits will allow us to study quickly and efficiently own objects and select interesting foreign objects.

The analysis of classification systems allows us to determine directions for further changes and harmonization of the national evaluation system. Until recently, social and environmental factors were rarely taken into account when classifying mineral reserves and resources. Their importance has grown significantly over the past few years. Many projects have been delayed or canceled because they did not meet social or environmental expectations, even if they met all other requirements of quantity, quality, and profitability. The various factors involved in the classification of resources do not exist in isolation but operate in a complex manner. In particular, specific issues of property rights and use of the resource, licensing conditions, and other legal issues, which as a result also create economic conditions, can be affected by social and environmental risks. The delay caused by the resolution of these issues in connection with socio-environmental problems can have a significant impact on the economics of projects and even make them economically unprofitable [3].

2. Results

Until recently, social and environmental factors have rarely been considered in the classification of natural resources. Their importance has grown considerably in the last few years. Many projects have been delayed or canceled because they failed to meet social or environmental expectations, even though they met all other requirements. The various factors involved in resource classification do not exist in isolation, and the distinction between them is rarely black and white. The related issues of ownership, contract terms, legal, regulatory issues, and in some cases, financial conditions may be affected by social and environmental issues. A delay due to the resolution of these as a result of socio-environmental issues can have a significant impact on the economics of projects, even making them no longer economically viable.

Socio-environmental issues, typically described as a requirement for “social license” or “social license to operate” (SLO), have attracted a significant amount of interest and attention in recent years. A project cannot proceed unless the important social and environmental contingencies are resolved, typically described as obtaining an SLO. UNFC is a tool for effective management of national resource endowments needed for realizing the Sustainable Development Goals (SDGs). UNFC applies to energy and mineral resources; injection projects for the geological storage of CO_2; and anthropogenic resources such as secondary resources recycled from residues and wastes. UNFC aims to provide necessary specifications and guidelines for optimizing the management and development of resources, with positive impacts on society, the environment, local economies, and employment [3].

In 2022, the problems and risks of social licenses have become especially acute, which is especially noted by the forecasts of global audit companies. Table 1 lists the Top 10 business risks and opportunities for mining and metals. The risks of social licenses appeared in the lists of top risks in 2015, but until 2022 they did not rise above 5th place.

With Ernst and Young’s (EY) data released at the end of 2022 [4], environmental, social, and corporate governance (ESG) remains a top risk and challenge for mining and metals companies in 2023. This issue is now widely included in corporate strategies due to its impact on almost all aspects of operations – productivity, logistics, economics and finance, sales markets, etc. Some of the biggest areas of ESG improvement are not new – ensuring diversity, equity, and inclusion still remain challenges, and mine closures and rehabilitation require longer-term, more strategic planning [4].

However, every year the demands on mining enterprises are becoming stricter and today, water resources management and biodiversity are fast becoming urgent priorities in the face of climate change. Stakeholders expect from companies a better assessment of risks and opportunities to minimize them with the help of transparent studies and guarantees for their

Table 1. Top 10 business risks and opportunities for mining and metals in 2017-2022 [4].

№	2023	2022	2021	2019-2020	2017-2018
1	Environment and social risk	Environment and social risk	License to operate	License to operate	Digital effectiveness
2	Geopolitics	Decarbonization	High Impact Risks/COVID-19	Digital effectiveness	Competitive shareholder returns
3	Climate change	License to operate	Productivity and Rising Costs	Maximizing portfolio returns	Cyber
4	License to operate	Geopolitics	Decarbonization	Cyber	New world commodities
5	Productivity and costs	Capital	Geopolitics	Rising costs	Regulatory risk
6	Supply chain disruption	Uncertain demand	Capital	Energy mix	Cash optimization
7	Workforce	Digital and innovation	Workforce	Workforce	Social license to operate
8	Capital	Workforce	Volatility	Disruption	Resource replacement
9	Digital and innovation	New business models	Digital and Data Automation	Fraud	Access to and optimization of energy
10	New business models	Productivity and costs	Innovation	New World commodities	Managing joint ventures

results. Stricter reporting will be critical if companies are to meet growing stakeholder expectations and avoid accusations of greenwashing. A bonus for companies that meet these requirements is significant competitive advantages — from access to capital and resources to obtaining a license to conduct activities and attracting highly qualified personnel [4].

Among the most significant for the extractive industry in the list of social and environmental factors were the following (in descending order): water resource management problems, compliance with the processes of decarbonization of production, reduction of the negative impact on climate change, environmental friendliness of production and volumes of emissions that are directly or indirectly related to enterprises, etc.

Classifications of mineral reserves and resources always reflect the most important features of mineral projects that determine their effectiveness. From the beginning, these were basic geological and mining technical characteristics, then economic and environmental factors. Now such a sign is environmental, social, and governance, which directly affect the possibility of project implementation. Next, we analyze existing system classifications to determine the direct and indirect ways in which these systems account for these ESG factors.

The development of international reporting standards for the assessment of mineral resources began at the end of the 20th century as a result of globalization processes in the extractive industry (figure 1). The largest mining companies are developing international projects and diversifying the regional risks of the mining business. This necessitated the development of integrated assessment systems that create unified and understandable tools for assessing mineral reserves and resources, regardless of the location of the assessment object itself.

This study analyzes and compares the classification features of various systems: Ukrainian classification [1], UNFC [2], The Petroleum Resources Management System (PRMS) [5], The Committee for Mineral Reserves International Reporting Standards (CRIRSCO) [6] in order

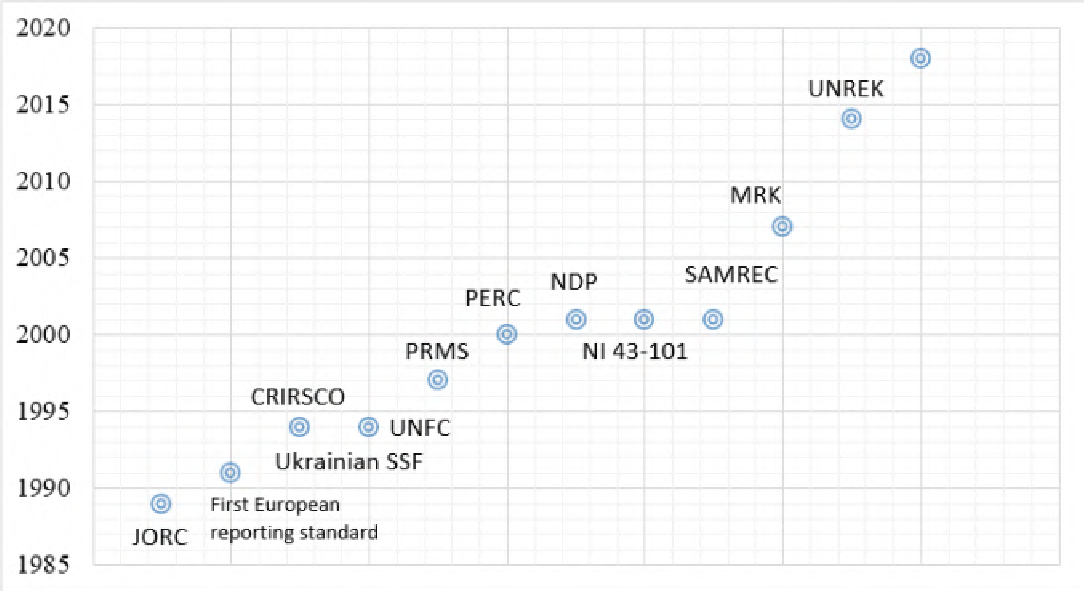

Figure 1. Development of international and national standards for mineral assessment in the period 1990-2020.

to establish features that allow determining the social and environmental risks of subsoil use projects.

In the mining projects valuation, environmental and social risks, as well as ESG in general, are often used in the context of investment attractiveness, although stakeholders include not only the investment environment, but also customers, suppliers, company personnel, local populations, and governments, who are increasingly interested in safe (in all senses), and stable development of organizations and companies on their territory. The presence of these direct features in the classification systems indicates the orientation of the assessment standards to the comprehensive assessment of projects as such meeting the goals of sustainable development.

Below are comparisons of the basic parameters of classification systems (table 2): CRIRSCO (by International reporting template for the public reporting of exploration targets, exploration results, mineral resources, and mineral reserves [6], PRMS Petroleum resources management system update 2018 [5], The Norwegian Petroleum Directorate's resource classification system (NPD) 2016 [7] Ukrainian Classifications of reserves and resources for minerals of the State Subsoil Fund (SSF) [1]. The features of classifications are given in the order in which they are considered in the system.

From the given comparison, it is fixed that the social and ecological viability of subsurface and natural resources projects is used as a direct feature only in the UNFC. In 1997, the UNFC was developed for solid minerals and conventional energy resources with the aim of becoming an ideal tool for comparing different regional and national standards. Currently, this classification has been expanded to include other types of resources. Today, the UNFC covers energy resources, including oil and gas; renewable energy projects; atomic energy resources; solid minerals; CO_2 storage projects; underground water; and anthropogenic resources, such as secondary resources recycled from production residues and wastes. An important feature is the systematization of information not only for geological and mining enterprises but also for all interested parties. Such parties are defined as international and regional organizations in the field of international research of mineral resources and energy (to facilitate the formulation of a consistent and visionary strategy of actions), national and local governments (for the sustainable

Table 2. Comparison of the basic features of the mineral resources classifications.

№	Standard/ document	UNFC	CRIRSCO	PRMS	NDP	Ukrainian SSF
1	Main types of mineral	Hydrocarbons (HC), minerals, water, nuclear fuels	Solid minerals	HC	HC	HC, Solid minerals
2	Unconventional types of minerals, other natural resources	Solar, wind, geothermal, hydro-marine, bioenergy, injection for storage	Mineralised Fill, Remnants, Pillars, Low Grade Mineralisation, Stockpiles, Dumps and Tailings	Unconventional resources CO_2 (2017)		Partially unconventional hydrocarbons
3	Object of classification and assessment	Projects (development or operation)	Mineral projects Resources and Reserves	Projects (exploration, appraisal, development) Resources and Reserves	Projects Resources and Reserves	Subsurface area Resources and Reserves
4	Person who carrying out a classification and evaluation	Competent person	Competent person, qualified person (NI 43-101)	Evaluator (independent consultants, employees)	Evaluator	Expert Group
	Main features of classification					
5	1)	Environmental-socio-economic viability	Level of geological knowledge and confidence	Project Status and Chance of Commerciality	Resource classes Petroleum volumes	Level of level of economic, social and industrial importance
	2)	Project feasibility	Modifying factors (mining, processing, metallurgical, infrastructure, economic, marketing, legal, environmental, social, and governmental)	Uncertainty	Project maturity	Stage of technical and economic development
	3)	Level of geological knowledge				Level of geological knowledge Complexity of geological structure as aditional feature
6	Start date	1997	1989 (JORC), 1994 (CRIRSCO)	2007	2001	1997
7	Last updated date	2019	2012 (JORC), 2019 (CRIRSCO)	2018	2016	2018
8	Main regions	Global	USA, Canada, Europe, Australia	USA, Europe	Norway	Ukraine
9	Implementation/ harmonization in Ukraine	Partially used in the investment projects	Partially used in the investment evaluation of projects	Partially implemented by oil and gas companies	–	Harmonized with UNFC

management of national resources), companies and industrial enterprises (for the development of production and technologies, project management and financing), financial organizations and funds (for project management and financing) [2, 3]. Thus, the UNFC itself is a tool for the effective management of national resources necessary for the realization of sustainable development goals, which enables all interested parties to find a common understanding of the development of resources and territories, as well as to compare projects in different types of resources and subsoil use. The development of the basic characteristics of the classification of reserves and resources in the UNFC from 1997 to 2020 is shown in the following table 3.

Table 3. Development of Principal elements of the UNFC.

	Year				
	1997	**2004**	**2009**	**2016**	**2019**
Principle Elements	Solid Fuels and Minerals	Previous	Previous + Oil, Gas, Uranium	Previous + Renewable project, incl. Geothermal	Previous + Bioenergy, Anthropogenic Resources
	Economic axis	Economic axis	Socio-economic viability	Socio-economic viability	Environmental-Socio-economic viability
	Feasibility axis	Feasibility axis	Project feasibility	Project feasibility	Project feasibility
	Geological axis	Geological axis	Geological knowledge	Geological knowledge	Geological knowledge

Other standards and classification systems have evolved in accordance with the more practical and rational objectives of providing reliable valuations for investors of all levels. The CRIRSCO standard notes that the extractive industry today is a global international business whose financial and operational success depends on the trust and confidence of investors [6]. Unlike many other industries, geology and mining deal with mineral resources that are exhaustible and non-renewable. The main emphasis on the risks of mining projects in these standards is made on geological risks, which depend on the reliability of information about objects from the beginning of the geological study to the end of mining. Subsoil users are encouraged to effectively and transparently assess the risks associated with investments to ensure the high level of confidence necessary to sustain their activities [6]. ESG criteria are taken into account as part of modifying factors that determine the possibility of converting mineral resources into reserves that are designed and have individual technical, technological, and organizational solutions for implementation, which forms their economic and environmental assessment in the relevant legal and regulatory conditions. In the hydrocarbon resource assessment standards 2018, the social and environmental component is also indirectly taken into account in the project success criteria ("chance" for commercial implementation) and uncertainty parameters.

3. Conclusions

The paper presents a comparison of classification features in the exploration and evaluation of mineral resources in domestic and international practice. This study analyzes and compares the classification features of various systems: The Ukrainian Classifications of reserves and resources for minerals of the State Subsoil Fund, The United Nations Framework Classification for Resources, The Petroleum Resources Management System, The Norwegian Petroleum Directorate's resource classification system, the Classification of the Committee for Mineral Reserves International Reporting Standards.

As a result, the most common feature of classifications is the level of geological study. This feature makes it possible to distinguish 4 groups of geological knowledge. Features of economic viability and status of the project, as a rule, are used in international practice. Important criteria, which are now reflected only in the UNFC, are the social and environmental viability of projects. This determines the importance of accounting for ESG in our valuation and resource accounting systems.

In recent years, social and environmental risks have become basic for the implementation of mining projects. Their growth can lead to the postponement of projects in time or the complete cancellation of decisions made because they did not meet social or environmental expectations, even if they met the requirements of quantity, quality, and profitability. Such changes must be reflected in classification systems for reserves and resources assessment that are used by all stakeholders to make management and investment decisions. Today, the social and ecological viability of subsurface and environmental projects is used as a direct feature only in the UNFC, and its inclusion took place in 2009 in the part of social factors, and in 2019 – in the part of environmental factors. This shows that the UNFC is a tool for the effective management of national resources, necessary for the realization of the goals of sustainable development, which enables all interested parties to find a common understanding of the development of resources and territories, as well as to compare projects in different types of resources and subsoil use.

In other international standards, as well as in the domestic classification of the State Subsoil Fund, the ESG criterion is taken into account indirectly, which is one of the key areas of development of these mineral resource evaluation systems. Such development can take place in two directions: 1) inclusion of social and ecological criteria of the direction as basic features, while this is possible both in the form of complex parameters and individual classes/subclasses; 2) use and improvement of existing methods of resource valuation, taking into account the environmental and social risks of the implementation of mining projects.

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References

[1] Cabinet of Ministers of Ukraine 1997 Classification of reserves and resources of minerals of the state subsoil fund URL https://zakon.rada.gov.ua/laws/show/432-97-%D0%BF#Text
[2] 2019 United Nations Framework Classification for Resources: Update 2019 UNECE Energy Series 61 United Nations Economic Commission for Europe Geneva URL https://unece.org/DAM/energy/se/pdfs/UNFC/publ/UNFC_ES61_Update_2019.pdf
[3] United Nations Economic Commission for Europe 2021 UNFC and Social and Environmental Management URL https://unece.org/unfc-and-social-and-environmental-management-0
[4] EYGM Limited 2021 Top 10 business risks and opportunities for mining and metals in 2022 URL https://assets.ey.com/content/dam/ey-sites/ey-com/en_gl/topics/mining-metals/ey-final-business-risks-and-opportunities-in-2022.pdf
[5] Society of Petroleum Engineers 2023 Petroleum Resources Management System URL https://petrowiki.spe.org/Petroleum_Resources_Management_System
[6] Committee for Mineral Reserves International Reporting Standards 2019 International reporting template for the public reporting of exploration targets, exploration results, mineral resources and mineral reserves URL https://www.crirsco.com/docs/CRIRSCO_International_Reporting_Template_November_2019.pdf
[7] Andersen T, Bjørheim M, Blystad P, Bygdevoll J and Knudsen K R 2018 The Norwegian Petroleum Directorate's resource classification system 2016 Report NPD-07-16 Norwegian Petroleum Directorate URL https://www.npd.no/globalassets/1-npd/regelverk/forskrifter/en/classification-of-petroleum-resources.pdf

Mathematical tools of solving the problem of restoring the surface distribution of radiation pollution based on remote measurement data

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Mathematical tools of solving the problem of restoring the surface distribution of radiation pollution based on remote measurement data

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Abstract. The modern achievements in the construction of small flying machines cause the active development of remote monitoring, in particular geophysical airborne gamma-ray spectrometer surveying. Such observations are important, since large amounts of man-made radioactive materials get into the environment, especially during accidents like at the Chornobyl or Fukushima nuclear plants. On the other hand, the natural distribution of radioactive sources is inhomogeneous and can provide us with useful information about the soil structure. One of the problems appearing at the handle of information collected with unmanned aerial vehicles concerns the correction of readings to identify the peculiarities of gamma-ray fields. To perform this, the analytical method based on the solution of the inverse problem formulated in terms of integral relation is used. In this research, to reconstruct the surface distribution of the gamma-ray field, the Tikhonov and Landweber techniques are applied. It is shown that these algorithms allow one to distinguish radioactive hot-spots located closely.

1. Introduction

To support the sustainable development of economies and human societies, the effective implementation of innovative technologies, methods of rational nature management, and safety components should be realized. To a large extent, this applies to handling the radioactive materials which can provide significant benefits and at the same time can cause substantial damage. To organize the effective control of radioactive materials accompanied by ensuring radiation safety, the novel achievements in the fields of remote sensing and information technologies [1–4] can be useful. There are many different means for gathering and processing information on observed objects including satellites, manned aviation, ground observation, and etc. [5]. Among them, the small flying machines or so-called unmanned aerial vehicles (UAVs) should be noted, the use of which has developed rapidly due to their advantages [1,6–9] including the possibility to reveal the size-limited gamma-ray anomalies [10].

Nevertheless, the collected data undergo the influence of different effects, i.e. UAV velocity and high, detector's properties, attenuation, natural radiation, and require further processing and corrections. To improve the quality of UAV measurements, it is utilized the approach [11–15] which is based on the use of a solution of inverse problem. This problem involves a multiple integral relation, approximation of which, in turn, causes well-known problems. However, the main obstacle relates to the construction of a solution to the inverse problem, since we deal with an ill-posed problem that produces strong instability, oversmoothing effects, and etc. To overcome this difficulty, many techniques have been developed including the Tikhonov and Landweber algorithms, which we used in these studies.

2. Research aim and objectives

In this research, we consider the adaptation of algorithms for the inverse problem which arises during the remote monitoring of distributed radioactive (namely gamma-ray) fields. In particular, restoration of the gamma field, distributed over the ground surface, and identification of its peculiarities (local intensities) are performed.

3. Statement of the problem

As known from numerous experiments [15–17], the readings of airborne detector require some corrections. One of the possible ways to do this is the inversion of airborne data using the algorithm of the proper inverse problem. The mathematical statement of this problem involves the integral relation describing the attenuation of the gamma radiation with distance from the ground surface, the distribution of radioelement sources in the ground, and the detector's properties. The UAV velocity also should be taken into account.

Thus, consider the simplified scheme (figure 1(a)) of remote sensing, continuing our studies presented in [6]. A small flying machine is equipped with a detector providing us the counting of gammas emitted from the ground surface. UAV moves along the axis Ox with the velocity v. It is marked by the point D with the coordinates (x^d, y^d) and the altitude h^d in figure 1(a).

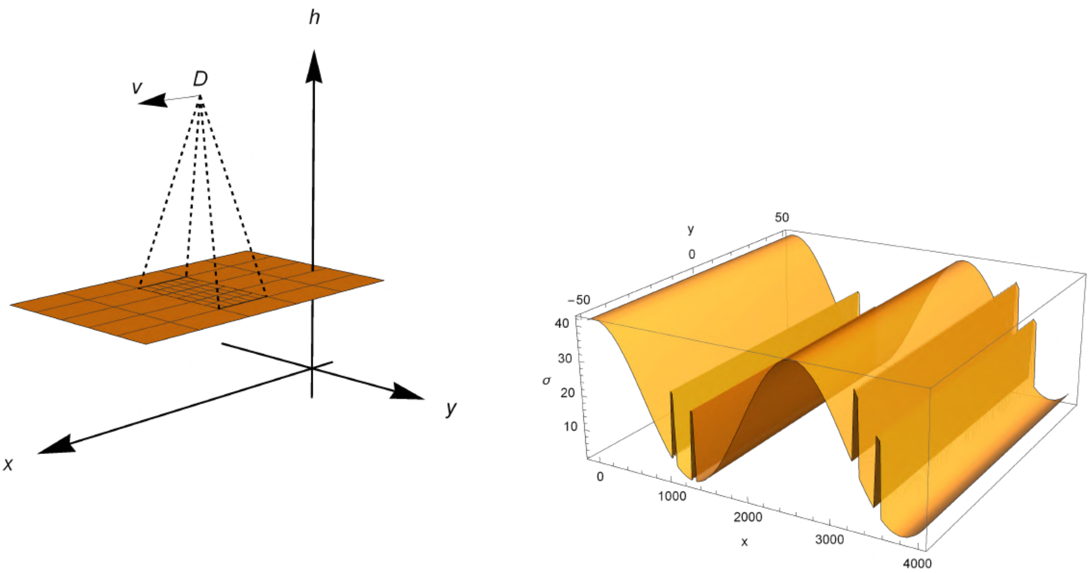
Let us assume that the detector's eyeshot is formed by the collimator with a rectangular cross-section and the aperture 2θ rad. Then the view window appearing on the ground surface is almost rectangular. The size of this window depends on the detector's altitude h^d and θ. The elementary geometric reasoning leads us to the simple relation for the window side $2\Delta x = 2\Delta y = 2(h^d - h)\tan\theta$, where $h(x, y)$ stands for the relief altitude. Dealing, for instance, with the detector with $\theta = \pi/3$ rad located at a height of 55 m above the ground surface, the view window size is $2\Delta x = 190$ m.

During a flight, the detector collects gammas and fixes the number of gamma quants $W(t_i)$ at discrete moments of time t_i, $i = 1, 2, \dots, N$. For the sake of simplicity we will assume that all time intervals $[t_{i-1}; t_i]$ are of the same length and, therefore, the detector's exposure time is $t_i - t_{i-1} = \tau = const$. Thus, if we fixed $\tau = 1$ s and $v = 27$ m/s (about 100 km/h), then UAV flying $L = 4000$ m provides us with $L/(\tau v) \approx 140 \equiv N$ values of W.

Thus, in general, to evaluate the number of trapped gamma rays at a time moment t_i, it can be used the following integral [3, 11–13, 15, 16] equation

$$\Lambda \int\limits_{t_{i-1}}^{t_i} dt \int\limits_{\Omega} \sigma(X)\, \Phi\left(X^d, X\right) d\Omega = W(t_i), \qquad i = 1, \dots, N, \tag{1}$$

where σ is the density of gamma sources; $X^d = (x^d, y^d) \in R^2$ is the detector's position and



(a) (b)

Figure 1. The simplified scheme of remote sensing (a) and the surface of the function $\sigma(x, y)$ – the density of gamma sources (b).

$X = (x, y) \in R^2$ is a point in the domain Ω representing a radioactive material; Λ is the scaling factor depending on the geometric and physical properties of detector.

The quantity

$$\Phi = \phi\left(X^d, X\right) \frac{e^{-r\mu}}{4\pi r^2},$$

where μ is the coefficient of attenuation in air; the function $\phi = (h^d - h)/r$ coincides with the cosine of angle between the vertical and the direction from the detector to the point X; $r = \sqrt{(h^d - h)^2 + (x^d - x)^2 + (y^d - y)^2}$ is the distance between detector and the point X lying on the surface.

Thus, the problem arises: to restore the surface distribution $\sigma(x, y)$, when the data W are given. This is a well-known *inverse* problem.

4. Construction of the algorithms for the inverse problem

Before solving the inverse problem, we prepare the test data W for checking the quality of the algorithm's work. In fact, evaluating the quantities $W(t_i)$, the *forward* problem is solved. Thus, we specify the function of radioactive sources density

$$\begin{aligned}\sigma(x, y) =& 20\left(\cos\left[\frac{x}{400}\right] + 1.1\right) + 20\,UnitBox\left[\frac{x - 3500}{50}\right] + 20UnitBox\left[\frac{x - 3250}{50}\right] + \\ &+ 20UnitBox\left[\frac{x - 1000}{50}\right] + 20UnitBox\left[\frac{x - 1250}{50}\right],\end{aligned} \tag{2}$$

where $UnitBox[z]$ stands for the in-built *Mathematica* package function, equal to 1 for $|z| \leq 1/2$ and 0 otherwise.

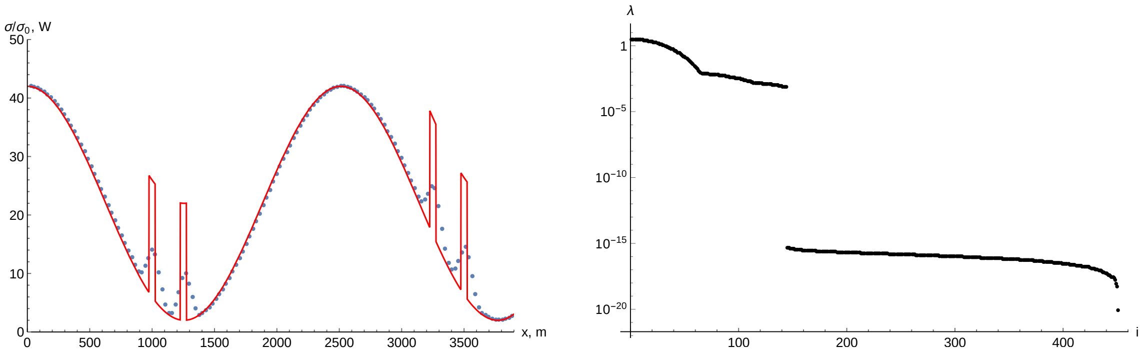
Using the function $UnitBox[z]$, we model the localized sources of high radioactivity. In other words, four peaks on the density function σ can represent, for instance, trenches containing radioactive waste. Actually, in this research, the function (2) doesn't depend on y and its graph is depicted in figure 1(b). The model (1) also requires the parameter $\mu = 0.001$ 1/m; relief profile $h(x, y) = 20$ m; UAV altitude $h = 75$ m. Although we can incorporate in relation (1) the UAV specified velocity v_i at each interval $[t_{i-1}, t_i]$, but in this research we neglect small deviations of UAV velocity and it is assumed that the UAV moves all flight time with the mean constant velocity $v = const$. Since the UAV's movement is performed along the axis Ox, its coordinate $y^d = 0$.

Then, substituting the new variable $u = vt$ and other parameters and functions into relation (1), we get

$$W_i = \frac{\Lambda}{v} \int\limits_{(i-1)\tau v}^{i\tau v} du \int\limits_{i\tau v-\Delta x}^{i\tau v+\Delta x} dx \int\limits_{-\Delta y}^{\Delta y} dy\, \sigma(x, y) \frac{(h^d - h)}{4\pi r^3} e^{-r\mu}, \qquad i = 1, \ldots, N, \tag{3}$$

where $t_i = \tau i$, $r = \sqrt{(h^d - h)^2 + (x^d - x)^2 + (y^d - y)^2}$. In *Mathematica* package, the relation (3) is evaluated by means of the function *NIntegrate[]*.

For convenience, we take $\Lambda = \sigma(0, 0)/W_1$, in order to normalize data and to compare with the parent distribution σ. Figure 2(a) represents the comparison of the exact graph of the density function σ and data W.



(a) (b)

Figure 2. The comparison of the profile of the function (2) and data W evaluated by the formula (3).

Now, to develop the algorithm for the inverse problem solution, we discretize the integral relation (3) using the rectangle method:

$$\int\limits_a^b f(x)dx = \Delta_0 \sum_{k=1}^{n} f\left(a + \frac{2k-1}{2}\Delta_0\right), \qquad \Delta_0 = \frac{b-a}{n}. \tag{4}$$

Applying formula (4), the approximation of integral (3) can be cast in the following form

$$\begin{aligned} &W_i = \frac{\delta_x \delta_d \delta_y}{v} \sum_{k=1}^{N_2} \sum_{j=1}^{N_1} \sigma(x) \sum_{\ell=1}^{N_y} \Phi\left(x, y, x^d, y^d\right); \\ &x = (i-1)\tau v + \frac{2j-1}{2}\delta_d + \frac{2k-1}{2}\delta_x - \Delta x; \qquad y = -\Delta y + \frac{2\ell-1}{2}\delta_y; \\ &x^d = (i-1)\tau v + \frac{2j-1}{2}\delta_d; \qquad y^d = 0, \end{aligned} \tag{5}$$

where $\delta_x = 2\Delta x/N_2$, $\delta_d = \tau v/N_1$, and $\delta_y = 2\Delta y/N_y$.

Before using relation (5), we transform the argument x of σ in such a way that it will be multiple of the spatial step δ_x. Thus, let us assume that $\tau v = q\delta_x$, $\delta_d = p\delta_x$, $\Delta x = \varepsilon\delta_x$, where q, p, ε are natural numbers. Assuming that $q = [\tau v/\delta_x] \equiv N_1$, $r = 1$, $\varepsilon = [\Delta x/\delta_x] \equiv N_2/2$, where the function $[\cdot]$ returns an integer part of its argument.

Next,

$$x = (i-1)\tau v + \frac{2j-1}{2}\delta_d + \frac{2k-1}{2}\delta_x - \Delta x = \frac{\delta_x}{2}\left[2(i-1)q + (2j-1)p + (2k-1) - 2\varepsilon\right].$$

Since $i, q, j, p, k, \varepsilon$ are natural numbers, then the set of unknown values $\sigma(x)$ is defined for the multiple values δ_x.

Then, putting $\sigma(\frac{\delta_x}{2}\left[2(i-1)q + (2j-1)p + (2k-1) - 2\varepsilon\right]) = \sigma_f$, where $f = 2(i-1)q + (2j-1)p + (2k-1) - 2\nu$ are natural, the relations (5) can be presented in the form

$$W_i = \frac{\delta_x\delta_d\delta_y}{v}\sum_{k=1}^{N_2}\sum_{j=1}^{N_1}\sigma_f\sum_{\ell=1}^{N_y}\Phi_{i,k,j,\ell}, \tag{6}$$

which is the linear system of algebraic equations with respect to σ_f.

This system can be written in the matrix form

$$w = Kg, \tag{7}$$

where $w = (W_1, \ldots, W_N)^\top$, $g = (\sigma_{2-2\varepsilon}, \sigma_{4-2\varepsilon}, \ldots \sigma_{2(Nq+\varepsilon-1)})^\top$.

For instance, if we fix $\delta_x = 9$ m, then $q = 3$, $\varepsilon = 10$, $\tau = 1$ s, $v = 27$ m/s, $N = 144$, then structure of the system (6) can be understood from the first two equations

$$\begin{aligned} W_1 &= K_{1,1}\sigma_{-18} + K_{1,2}\sigma_{-16} + K_{1,3}\sigma_{-14} + K_{1,4}\sigma_{-12} + K_{1,5}\sigma_{-10} + \cdots + K_{1,22}\sigma_{24}, \\ W_2 &= K_{2,4}\sigma_{-12} + K_{2,5}\sigma_{-10} + \cdots + K_{2,25}\sigma_{30}. \end{aligned}$$

We see that the system is the set of *coupled* equations. The matrix K is multi-diagonal and not square, in general. This means that the system does not possess the unique solution and as a rule it is ill-conditioning. To obtain the proper solution in this case, the regularized algorithms are used. In this research, we apply the Tikhonov and Landweber algorithms [18].

4.1. Tikhonov method

Let us recall shortly that the Tikhonov regularization technique is based on the singular value decomposition (SVD) procedure applied to the matrix K and elimination of singular elements from the system's solution which produce the solution's instability. As shown in [18], using the SVD presentation of the $m \times n$ real-valued matrix K in the form $K = U\Sigma V^\top$, where U and V are the $m\times m$ and $n\times n$ unitary matrices respectively, $\Sigma = diag(\lambda_i)$ is the $m\times n$ diagonal matrix with diagonal nonnegative entries λ_i called singular values of K. Then the solution of system (7) can be cast in the matrix form $g = V \cdot diag(\lambda_i^{-1}) \cdot U^\top \cdot w$. To get rid of small singular values of the matrix $diag(\lambda_i^{-1})$, the Tikhonov filter function transforming the small singular values is used. Thus, instead of exact system's solution we have

$$g \approx g_\alpha = V \cdot diag((\lambda_i^2 + \alpha)^{-1}) \cdot U^\top \cdot w.$$

Using the identity $K^\top K + \alpha I = V \cdot (\lambda_i^2 + \alpha) \cdot V^\top$, where I is the unit matrix, the preceding relation reads as follows

$$g_\alpha = (K^\top K + \alpha I)^{-1} K^\top \cdot w, \tag{8}$$

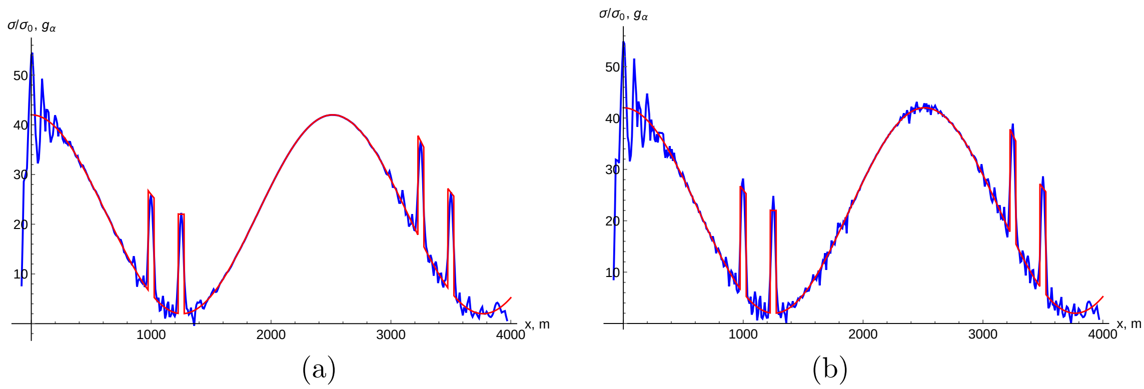


Figure 3. The comparison of the profile of the function (2) and the restored data g_α evaluated by formula (8). Here $\alpha = 10^{-3}$ (a) and $\alpha = 0.5 \cdot 10^{-8}$ (b).

where α is a regularization parameter.

Thus, at first consider the properties of matrix K used in this research. Instead of direct evaluation of K's singular values, it is simpler to evaluate eigenvalues of $K^\top K$ using the in-built *Mathematica* function *Eigenvalues*[]. The resulting distribution of eigenvalues λ_i^2 is presented in figure 2(a) (here the semilogarithmic plot is used) and shows the presence of small singular values for large i. Finally, putting $\alpha = 10^{-3}$, the solution (8) is evaluated and after rearranging $((-20+2j)hx/2; (g_\alpha)_j)$, $j = 1, \ldots, N$ the figure 3(a) is plotted. When α decreases up to $0.5 \cdot 10^{-8}$, the solution (8) is depicted in figure 3(b) and the growth of spurious fluctuations is observed. It means that α is too small.

In these studies we also are interested in the solution when the components of system (7) are desturbed by noise modeled with the random normally distributed numbers ξ. Thus, we consider the system (7) in the form $w = (K+\xi)g$, where $\xi \sim Norm(0, b)$. If we take the standard deviation $b = 5 \cdot 10^{-4}$, the *Mathematica* function *RandomVariate[NormalDistribution*[0, *b*], *Nq*] generates Nq random numbers. The random data histogram is depicted in figure 4(b) and tells us about a good approximation of normal distribution. As expected, the corresponding solution of inverse problem plotted in figure 4(a) shows more irregularity in comparison with the non-noised solution from figure 3. When $b = 0.001$ and random numbers undergo a greater deviations from their mean value (figure 4(d)), the solution (8) drawn in figure 4(c) becomes even greater irregularity, so that doublet structures become faintly visible against the background of fluctuations. The similar solution's behaviour is observed, when noise is added to the vector w in system (7) but at the smaller values of b.

4.2. Landweber method

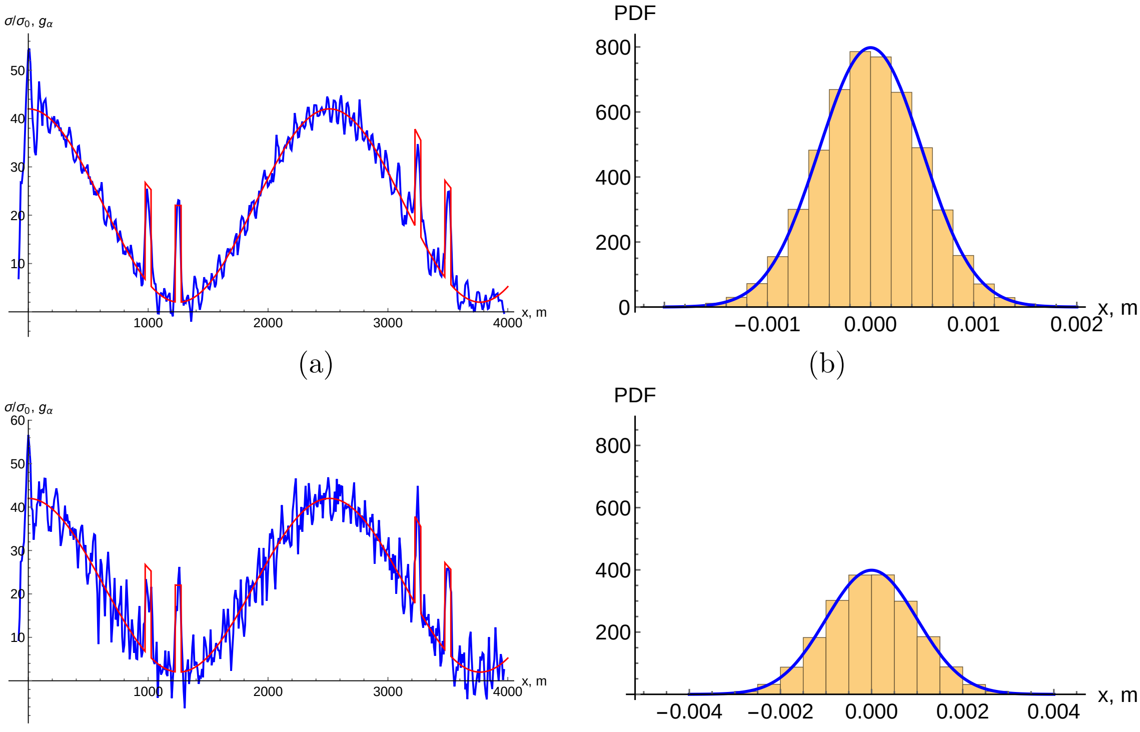
This technique belongs to the iterative regularization methods and is written in the form of iterative procedure [18]

$$(g_\alpha)_{\nu+1} = (g_\alpha)_\nu - \eta \cdot \operatorname{grad} J((g_\alpha)_\nu), \qquad \nu = 0, 1, \ldots, \tag{9}$$

where $J = \|K \cdot g - w\|^2/2$, $\operatorname{grad} J = K^\top \cdot (K \cdot g - w)$, η is a scalar controlling the speed of iteration convergence.

As shown in [18], the procedure (9) can be reduced to the matrix representation

$$(g_\alpha)_\nu = \eta \sum_{j=0}^{\nu-1} \left(I - \eta K^\top K\right)^j K^\top \cdot w. \tag{10}$$

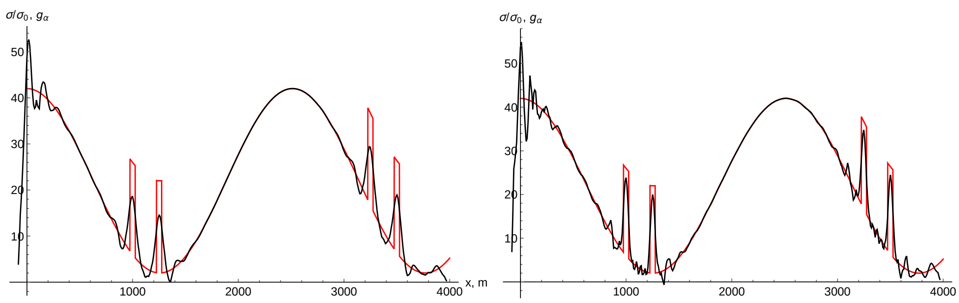


(a) (b) (c) (d)

Figure 4. Tikhonov method. Inverse problem solution (8) when noise is added. Here the standard deviations are $b = 5 \cdot 10^{-4}$ (b) and $b = 0.001$ (d).

Let us first fix not large iteration number $\nu = 50$. Then the corresponding solution (10) is shown in figure 5(a) and represents a good discrimination of the doublet pairs.

When the number of iterations are sufficiently large, i.e. $\nu = 500$, the solution (9) is plotted in figure 5(b). We see that the difference between exact solution and its approximation becomes smaller. It should be noted that the development spurious oscillations at the left edge of the interval, whereas the solution at the right edge behaves well. The reason for this instability requires additional studies, although this effect does not influence the hot-spot detection.



(a) (b)

Figure 5. The Landweber algorithm. The profiles of g_ν defined by (10) evaluated at $\nu = 50$ (a) and $\nu = 500$ (b). Here $\eta = 0.4$.

5. Concluding remarks

Thus, the research outlined above dealt with the mathematical issues devoted to the remote sensing areas contaminated by the highly radioactive materials. Nowadays the use of UAVs for remote sensing grows rapidly, therefore, support and assistance of UAV technology are extremely important. To do this, modern software and numerical methods are utilized. In particular, the software *Mathematica* package offers the tools for constructing the solutions of forward and inverse integral problems in a simple way.

Using this package, we adopted the Tikhonov and Landeweber algorithms for the inverse problem and applied them to the test problem which takes into account the surface density distribution of gamma sources with doublet structures, while other quantities were chosen as simply as possible. It turned out that the algorithms for the inverse problem reconstruct the close doublet structures quite well, remaining them separated.

Presented studies can be used for organizing the monitoring of the territories with man-made radioactive waste, for instance affected by accidents at nuclear NPPs [14]. As is well known [6], the territory of the Chornobyl Exclusion Zone contains huge amounts of spent nuclear fuel, radioactive waste, and its temporary localization. These storage facilities consist of complex “Vector”, radioactive waste disposal points “Buryakivka”, “Pidlisnyi”, “ChNPP Stage III”, nine temporary radioactive waste confinement sites with a total area about 10 hectares and include nearsurface disposal facility, trenches, and mound storages. In order to distinguish the contours of lost trenches, the use of presented findings is promising.

The results obtained can be interesting for the experts in the fields of remote sensing of radiation, homeland security, ecology, nuclear medicine, and etc.

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References

[1] Connor D, Martin P G and Scott T B 2016 *International Journal of Remote Sensing* **37**(24) 5953–5987 URL https://doi.org/10.1080/01431161.2016.1252474
[2] Popov O O, Kyrylenko Y O, Kameneva I P, Iatsyshyn A V, Iatsyshyn A V, Kovach V O, Artemchuk V O, Bliznyuk V N and Kiv A E 2022 *CTE Workshop Proceedings* **9** 306–322 URL https://doi.org/10.55056/cte.122
[3] Catapano I, Gennarelli G, Ludeno G, Noviello C, Esposito G, Renga A, Fasano G and Soldovieri F 2020 *Remote Sensing* **12**(5) 774 URL https://doi.org/10.3390/rs12050774
[4] Liao X, Ye H, Xu C, Tan J and Yue H 2020 *IOP Conference Series: Earth and Environmental Science* **502**(1) 012009 URL https://doi.org/10.1088/1755-1315/502/1/012009
[5] Marques L, Vale A and Vaz P 2021 *Sensors* **21**(4) 1051 URL https://doi.org/10.3390/s21041051
[6] Zabulonov Y L, Popov O O, Skurativskyi S I, Bondar O I, Iatsyshyn A V and Molitor N 2022 *IOP Conference Series: Earth and Environmental Science* **1049**(1) 012015 URL https://doi.org/10.1088/1755-1315/1049/1/012015

[7] Xiang T Z, Xia G S and Zhang L 2019 *IEEE Geoscience and Remote Sensing Magazine* **7**(3) 29–63 URL `https://doi.org/10.1109/mgrs.2019.2918840`
[8] Babak V P, Babak S V, Eremenko V S, Kuts Y V, Myslovych M V, Scherbak L M and Zaporozhets A O 2021 Monitoring the Air Pollution with UAVs *Models and Measures in Measurements and Monitoring* (Cham: Springer International Publishing) pp 191–225 URL `https://doi.org/10.1007/978-3-030-70783-5_7`
[9] Kolster M E, Wigh M D, Lima Simões da Silva E, Vilhelmsen T B and Dossing A 2022 *Remote Sensing* **14** 1134 URL `https://doi.org/10.3390/rs14051134`
[10] Salek O, Matolin M and Gryc L 2018 *Journal of Environmental Radioactivity* **182** 101–107 URL `https://doi.org/10.1016/j.jenvrad.2017.11.033`
[11] Minty B R S 1997 *AGSO Journal of Australian geology & geophysics* **17**(2) 39–50 URL `https://inis.iaea.org/search/search.aspx?orig_q=RN:28049082`
[12] Druker E 2017 *Journal of Environmental Radioactivity* **177** 13–23 URL `https://doi.org/10.1016/j.jenvrad.2017.05.006`
[13] van der Veeke S, Limburg J, Koomans R L, Söderström M, de Waal S N and van der Graaf E R 2021 *Journal of Environmental Radioactivity* **231** 106545 URL `https://doi.org/10.1016/j.jenvrad.2021.106545`
[14] Sasaki M, Ishizaki A and Sanada Y 2019 *Progress in Nuclear Science and Technology* **6** 63–67 URL `http://dx.doi.org/10.15669/pnst.6.63`
[15] Weihermann J D, Oliveira S P, Ferreira F J F and Silva A M 2019 Inverting airborne gamma-ray spectrometry data of Maricá calibration range, Brazil *16th International Congress of the Brazilian Geophysical Society* (Sociedade Brasileira de Geofísica) pp 1–6 URL `https://doi.org/10.22564/16cisbgf2019.173`
[16] Zabulonov Y, Popov O, Burtniak V, Iatsyshyn A, Kovach V and Iatsyshyn A 2021 Innovative Developments to Solve Major Aspects of Environmental and Radiation Safety of Ukraine *Systems, Decision and Control in Energy II* ed Zaporozhets A and Artemchuk V (Cham: Springer International Publishing) pp 273–292 URL `https://doi.org/10.1007/978-3-030-69189-9_16`
[17] Minty B and Brodie R 2016 *Exploration Geophysics* **47**(2) 150–157 URL `https://doi.org/10.1071/EG14110`
[18] Vogel C R 2002 *Computational Methods for Inverse Problems* (Society for Industrial and Applied Mathematics) URL `https://doi.org/10.1137/1.9780898717570`

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Development of a conceptual scheme for the creation of environmentally friendly Gd-containing neutron-absorbing nanocomposites

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Development of a conceptual scheme for the creation of environmentally friendly Gd-containing neutron-absorbing nanocomposites

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Abstract. The nature and properties of neutron radiation impose specific requirements on the creation and operation of such materials. The presence of accompanying and induced radiation, weather conditions, as well as the peculiarities of the location of functional layers require a hierarchical approach to the development of such neutron-absorbing materials. It was shown that the conceptual scheme of creating Gd-containing protective materials consists in taking into account all factors of their operation. In particular, it is shown that the presence of neutron-absorbing components is a necessary but not sufficient condition for their successful application in environmental conditions. In this work, Gd-containing chitosan films were prepared as an example of the proposed conceptual scheme for the creation of environmentally friendly neutron-absorbing nanocomposites. The prepared Gd films were characterized and their neutron permeability was estimated. The approach presented in this work contributes to the development of sustainable and responsible production practices, supporting SDGs 9 and 12.

1. Introduction

The need for protection against neutron radiation is due to the increasing level of radiation load. The growing level of radiation danger is associated with the rapid progress of science and technology and the expansion of the spectrum of the use of radiation technologies in the industry. Examples of such applications are non-destructive testing systems (cargo and car scanners), high-energy particle detectors (CERN), creation of new radiation sources (subcritical assembly "Neutron Source", Kharkiv, Ukraine) and compact nuclear power plants.

The need for protection against neutron radiation is also urgent in space, where protection against cosmic radiation (high-energy heavy particles) [1] during travel and equipment operation is important. The main task of neutron-absorbing materials is to cut off the neutron part of the spectrum during the collision with high-energy particles, which reduces the radiation load.

2. Analysis of research and publications

Nowadays, nuclear technologies are widely used all over the world, in particular for environmental protection [2], scientific research [3, 4], medical imaging and therapy [5], neutrons in the field of nuclear energy [6], agriculture [7], etc. Neutron radiation is one of the most dangerous types of radiation and poses a real danger to radiation workers and the public. Its impact on biological tissue leads to ionization of the material and, as a result, significant changes in the functionality of the cell or loss of the ability to recover. Other chemical elements can also be formed, including radionuclides that create induced radioactivity in the body. This problem is also relevant for nuclear installations because, to neutron irradiation, the equipment becomes radioactive and is unusable.

To solve the problem of exposure to neutron radiation, it is necessary to limit the duration of exposure, maximize the distance from the radiation source, and use shielding material [8]. Over the past few years, several studies have been conducted on various protective materials against the dangers of ionizing radiation [9]. According to scientific studies, shielding materials usually consist of a matrix and a filler. Frequency the matrices used are hydrogen-enriched polymers, cement and glass [10–13]. Examples of elements and their compounds that can be used as fillers for neutron shielding are boron, cadmium, and selenium [14–16]. However, the price of these fillers is relatively high. Concrete is not optimal because it is heavy, cracks easily, and is prone to voids. Glass has a limited range of potential as a protective material [10]. Hydrogen-enriched polymers are widely used as matrix materials for nuclear shields due to their lightweight, good manufacturability, and strong ability to slow down neutrons [13, 17]. However, cost-effective composite shields with hydrogen-rich polymer matrices should be further investigated as shielding materials against the dangers of neutron radiation [8].

It is worth noting that epoxy resin is often used as a matrix in radiation shielding materials due to its high hydrogen content, excellent processability, strong radiation resistance, and suitability for adding a lot of inexpensive shielding fillers [13, 17]. The paper [13] presents the use of some secondary metallurgical resources and epoxy resin for the preparation of composites for various types of radiation. However, the shielding mechanism in these multiphase composites was never been elucidated.

Natural isotopes of Gd have a high ability to capture neutrons. Two of the seven stable isotopes ^{155}Gd and ^{157}Gd have very high neutron capture cross sections (55,000 and 255,000 barn, respectively). ^{155}Gd has the highest neutron capture cross section among all stable elements of the periodic table. The neutron capture cross section of ^{155}Gd is 65 times higher than that of the widely known ^{10}B [18, 19]. In figure 1 shows the cross-section of neutron capture by boron and gadolinium isotopes depending on the neutron energy. When a neutron is absorbed in the Gd nucleus, complex transformations occur, as a result of which γ-quants are generated, which displace electrons from the inner levels. This leads to the emission of internal conversion electrons, Auger–Koster–Kronig electrons, as well as photons and γ-quants. Computer modeling of the Gd neutron capture reaction predicts the output of 1.83 γ-photons, 0.84 γ-quant, and 0.69 internal conversion electrons [20].

The latest achievements in the development of nano- and micro-composite materials for the protection of workers and equipment from neutron irradiation are covered in the book [22]. In particular, the use of powder fillers as neutron absorbers is considered. In particular, it has been shown that the use of samarium (Sm) and Gd as fillers is effective in terms of the intensity of their interaction with neutrons [23], but at high concentrations it can cause the release of a significant amount of secondary gamma radiation. In this case, additional measures should be taken to protect against gamma radiation. As an optimal solution, the use of mixed boron-

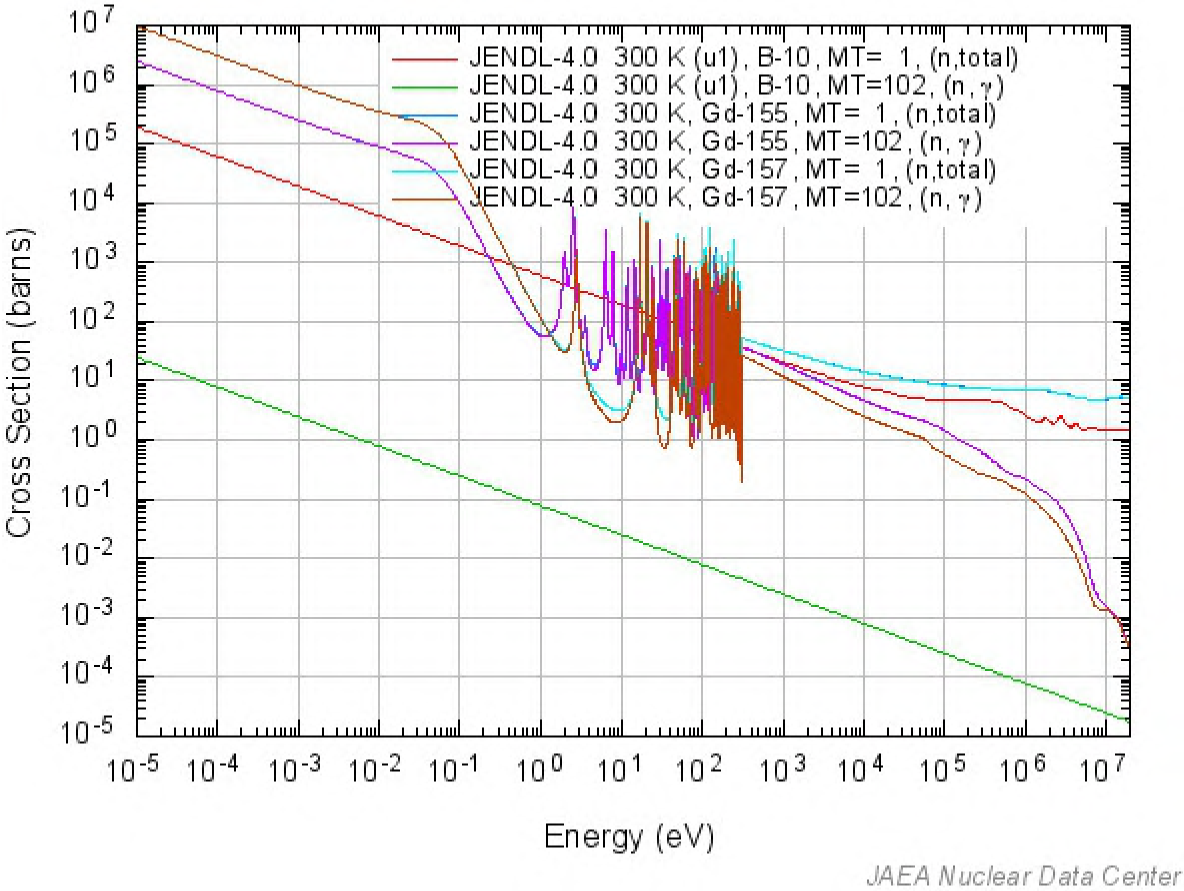

Figure 1. Section of neutron capture by ^{155}Gd, ^{157}Gd and ^{10}B isotopes [21].

gadolinium-containing fillers is proposed, which makes it possible to achieve optimal absorption of neutrons for different energy spectra and, accordingly, the release of an "optimized" amount of secondary radiation.

It is known from other literary sources that wood is a good adsorber of ionizing radiation [24]. In this regard, *it can be assumed that the use of wood in combination with Gd-containing materials is promising, since wood has good absorbing properties relative to secondary gamma radiation and, in addition, good structural properties.*

The use of thermoplastic composite materials for protection against neutrons in outer space is covered in [25]. Also, to protect workers and equipment from neutron radiation, it was proposed to use thermoset polymers filled with inorganic fillers. Methods of their production, properties and neutron shielding characteristics were analyzed [26].

The goal of this scientific article is to develop a conceptual scheme for the creation of environmentally friendly Gd-containing neutron-absorbing nanocomposites, and to validate this scheme through the preparation and characterization of Gd-containing chitosan films as a potential neutron shielding material.

This work, we believe, is contributing to sustainable development goals 9 (industry and innovation) since it offers an innovative approach for neutron shielding and 12 (responsible production) due to the possibility to develop environmentally friendly neutron-shielding materials.

3. Results and discussion

Neutron-shielding composite materials act as part of certain objects as components of protective structures. In particular, neutron-shielding composites can act as components of coatings, insulating, protective and structural materials, etc., to fulfill their functions. Accordingly, during the operation of materials containing neutron shielding composites, it is important to take into account the influence of various factors on them, including the environment [27]. Among the factors that can have a direct (negative) impact, it is worth highlighting:

- weather conditions;
- accompanying radiation (gamma radiation, beta particles);
- induced radiation (caused by the interaction of neutrons with matter);
- the factor of material properties change due to aging and mechanical stress, etc.;
- others.

In this context, the use of Gd-containing composites as part of protective materials seems most likely in two scenarios: indoor and in the open air.

Obviously, the use of neutron shields outdoors includes a set of parameters that are suitable for the indoor applications, plus a protective coating against weather conditions (humidity, solar radiation, temperature, etc.).

The basics of technologies and materials that are suitable for protection against weather conditions are well studied and worked out, so their detailed coverage here is unnecessary.

In particular, in figure 2, a four-component scheme is proposed, which consists of a protective coating (layer 1), an intermediate layer 2, a neutron protective layer 3, and a structural or main layer 4. An example of the arrangement of protective layers is shown in figure 2 below.

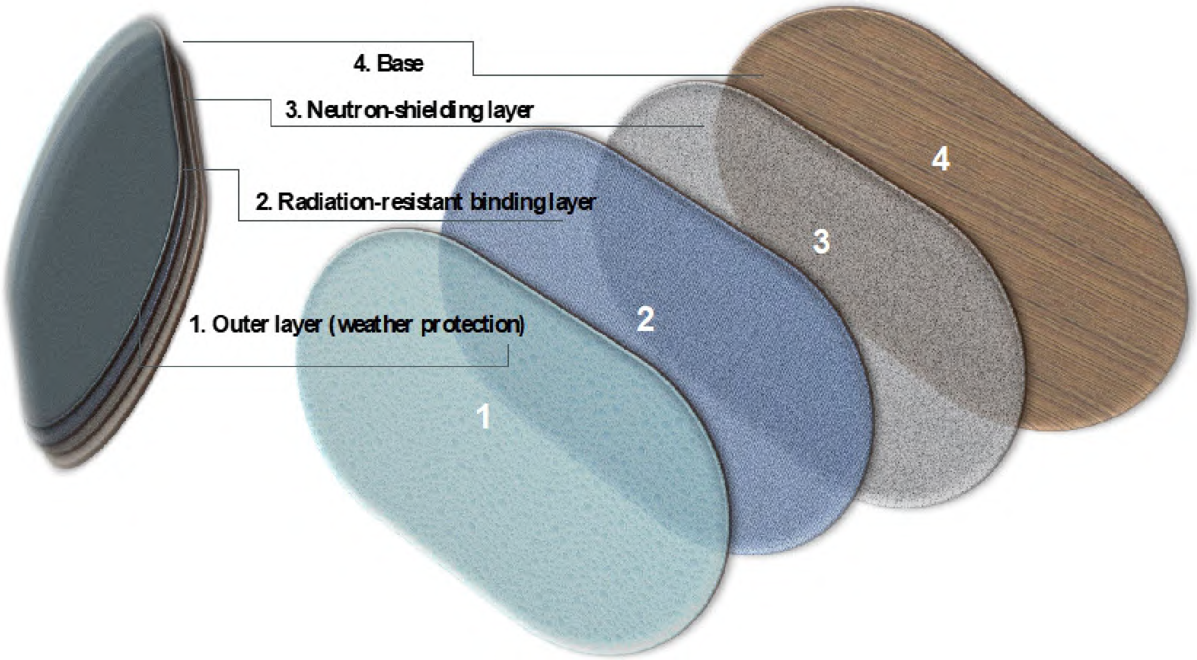

Figure 2. An example of proposed scheme of the arrangement of protective layers for a neutron-shielding composite material.

In addition to weather conditions, the impact of accompanying radiation is important, the presence of which should be expected at facilities with increased nuclear danger. It is important that the protection against accompanying radiation is at the front of the composite, for example as a protective paint, coating, varnish, etc. The radiation-resistant coating is applied to the base, which should ensure its reliable fixation and, accordingly, resistance to weather conditions. The basics of such technologies are well studied and worked out, so there is no need to cover them in detail in this project.

The base can be any material that meets the technical requirements, such as wood. Wood has good structural properties and is a sufficiently effective material for protection against gamma radiation.

The next layer can be directly Gd-containing neutron-absorbing composite material. The neutron protective layer should be located closest to the front of interaction with potential radiation sources. The work resource must exceed the maximum one-time load by several times. The thickness of the layer and the amount of neutron-shielding composite in it may vary depending on the specific purpose.

Taking into account the accompanying factors present during the operation of such composites in real conditions, it is also important to take into account other components of the interaction of neutrons with matter. It is worth noting that it is important to provide the neutron-absorbing composite material with a radiation-resistant shell several microns thick, made of a material that prevents the propagation of secondary electrons and neutralizes free radicals. It is worth noting that the formation of secondary electrons due to the interaction of neutrons with boron and gadolinium can cause the breaking of chemical bonds on a micrometer scale, and that is why it is important to “neutralize” such secondary electrons. Examples of such electron- and radical-absorbing materials can be cross-linked polymer hydrogels (for example, based on lignin) and surface-modified inorganic oxides (silica, magnetite, titanium oxide, etc.). The effective mileage (thickness of the substance layer that stops almost all particles) is given in table 1.

Table 1. Thickness of the layer of substance that stops most of $\beta-$particles.

Substance	**Electron energy, MeV**			
	0.05	**0.5**	**5**	**50**
	mean free path, cm			
Air	4.1	160	2000	17000
Water	$4.7 \cdot 10^{-3}$	0.19	2.6	19
Aluminum	$2 \cdot 10^{-3}$	0.056	0.95	4.3
Lead	$5 \cdot 10^{-4}$	0.02	0.3	1.25

The features of the structure of layer 3 and its interaction with neutron radiation are shown in the figure 3.

Beta particles (electrons and positrons) interact with electrons and nuclei in matter to a complete stop. The distance of beta particles depends on their energy.

When considering the use of neutron-shielding composite materials in protective structures, it is important to take into account various factors that can negatively impact the materials, such as weather conditions and accompanying radiation.

In this study, as chitosan films with and without Gd were prepared by a solution casting method. The films were cast from a chitosan solution containing the appropriate concentration of Gd salt, and then dried to obtain a thin film. The resulting films were characterized using scanning electron microscopy and their stability to electron beam was evaluated at the first stage.

The SEM micrograph in figure 4 shows the cross-sections of the chitosan film with and without the Gd, as a model of the Gd-containing neutron-absorbing composite material. The thickness of the film with Gd-containing composite material is 15 micrometers, while the thickness of the

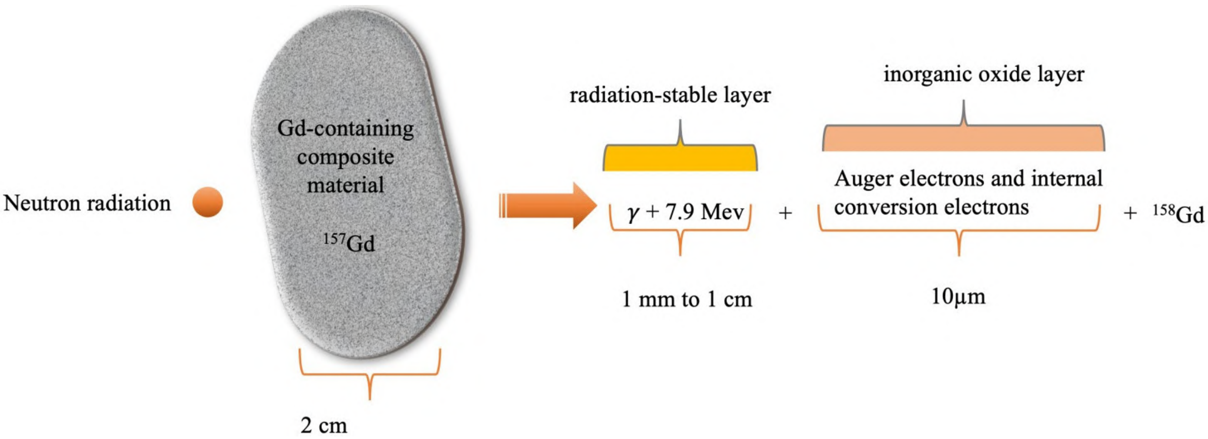

Figure 3. Radiation factors to be taken into account when developing a neutron shielding shell.

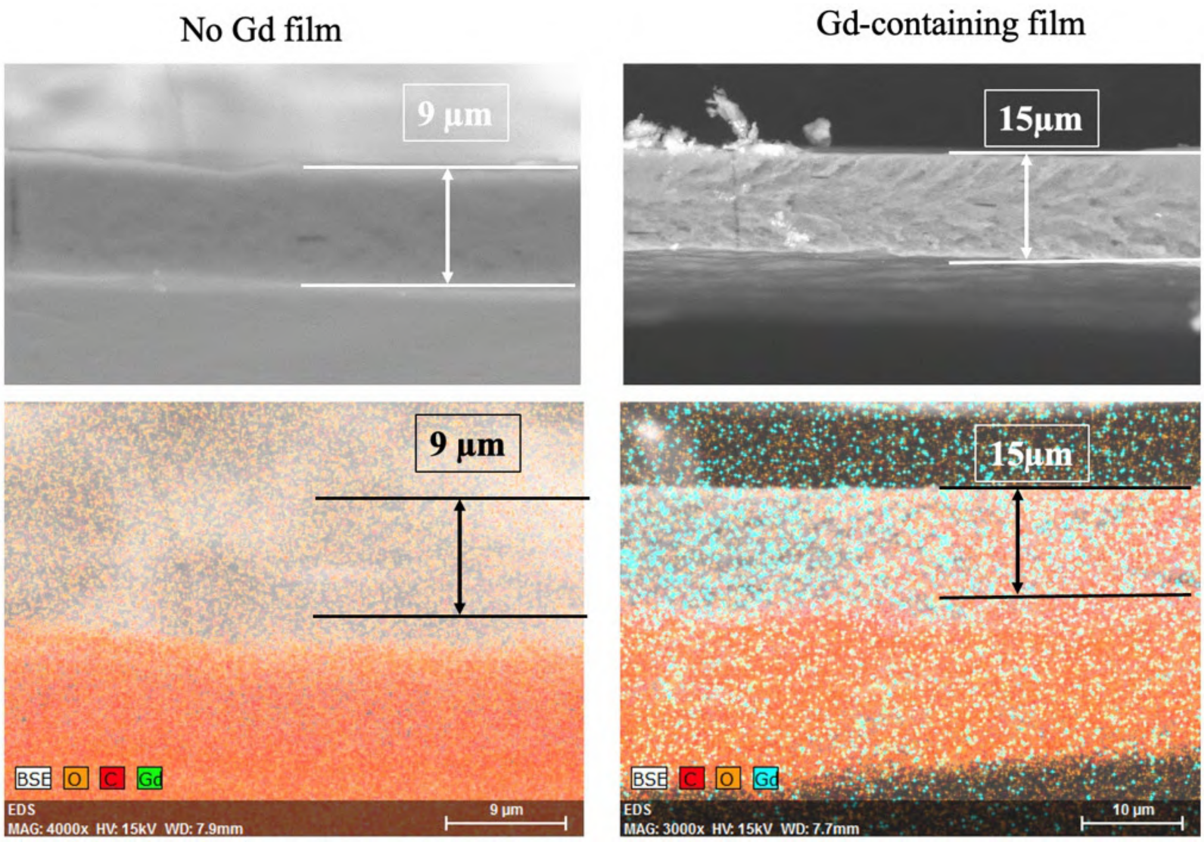

Figure 4. SEM micrograph of cross-sections of chitosan film with and without Gd-containing neutron-absorbing composite material.

film without Gd is only 9 micrometers. The element analysis (EDS) confirms the presence of Gd inside the film.

The results of this study suggest that chitosan, a natural polymer, can be used as a base material for the development of Gd-containing neutron shielding composites. The addition of Gd to the chitosan film increases its thickness and neutron shielding properties, making it a promising material for further development and application in neutron shielding.

The micrographs reveal the non-stability of the "just" chitosan film when exposed to the electron beam, as evident from the irregularities and deformations observed in the image (figure 5). In contrast, the Gd-containing chitosan film exhibits a more stable morphology under the same conditions, highlighting the potential of Gd as a stabilizing agent for natural polymer-based neutron shielding composites.

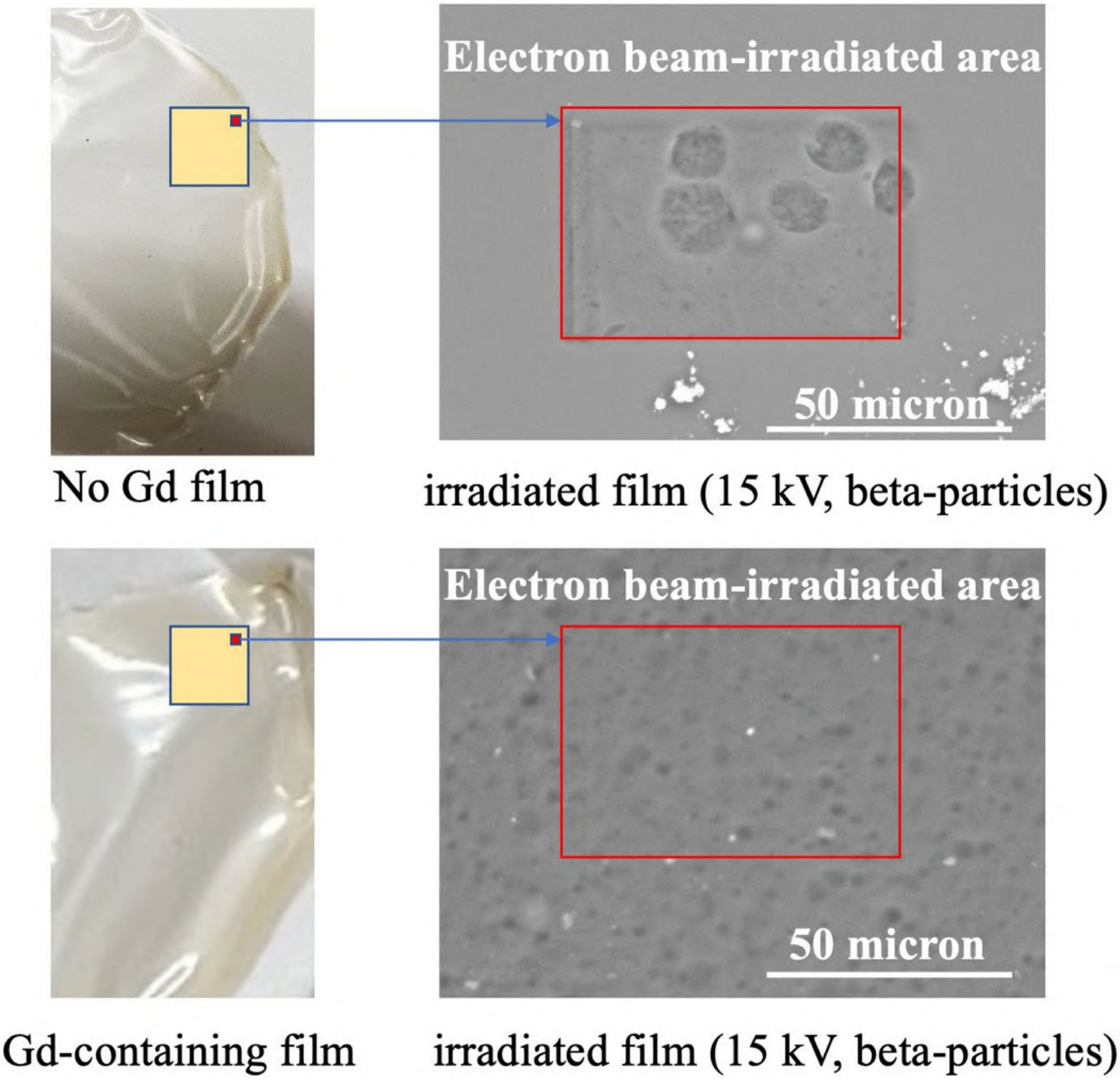

Figure 5. SEM micrographs of the cross-section of the chitosan film with and without Gd under electron beam.

The table 2 below compares the thickness, Gd content, and neutron shielding efficiency of the samples. The control sample (Chitosan) has a thickness of 9 μm and no Gd content. The Chitosan-Gd samples have a thickness of 15 μm and varying Gd content ranging from 3 wt% to 8 wt%. The neutron shielding efficiency of the samples is also provided, with the Chitosan-Gd samples showing increasing efficiency with increasing Gd content. This table helps to provide a concise overview of the properties of the different samples and facilitates easy comparison between them. This table helps to provide a concise overview of the properties of the different samples and facilitates easy comparison between them. The values for neutron permeability vere calculated according to [28] and are in good agreement with the data obtained in [29].

Table 2. Thickness comparison, Gd content, and neutron shielding efficiency of the samples.

Sampler	Thickness, (μm)	Gd content, (wt%)	Thermal neutron permeability, %
Control(Chitosan)	9	0	100
Chitosan-Gd	15	3	18.7
Chitosan-Gd	18	5	11.2
Chitosan-Gd	21	7	8
Chitosan-Gd	24	8	7

Further studies can be conducted to optimize the concentration of Gd within the film and to explore the feasibility of scaling up the production of such composites for practical use. It should be noted that the work described in this research paper represents only the beginning of the development and preliminary testing of the Gd-containing neutron shielding composites based on natural polymers such as chitosan and cellulose. Further research and testing are needed to optimize the composition and manufacturing process of these composites and to evaluate their performance under various environmental conditions and neutron radiation sources.

4. Conclusions

The nature and properties of neutron radiation impose specific requirements on the creation and operation of such materials. In particular, it is shown that the presence of neutron-absorbing components is a necessary but not sufficient condition for their successful application in environmental conditions. The presence of accompanying and induced radiation, weather conditions, as well as the peculiarities of the location of functional layers require a hierarchical approach to the development of such neutron-absorbing materials. As a result of literary data analysis, such an approach was proposed. It was shown that the principle scheme of creating Gd-containing protective materials consists in taking into account all factors of their operation. The approach, developed in this work is contributing to sustainable development goals 9 (industry and innovation) due to offering a more advanced and innovative approach for neutron shielding. Also, the development of environmentally friendly neutron-shielding materials contributes to SDG 12 (responsible production) due to decreased risk of the contamination of nature by toxic materials. The current study provides valuable insights into the potential of using chitosan as a matrix for Gd-containing composites and demonstrates the successful incorporation of Gd into the chitosan film as shown in the SEM images and EDS analysis. However, more extensive testing and evaluation of the material properties and performance are necessary to determine the feasibility and practical applications of these composites in real-world scenarios.

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References

[1] Cataldo F and Prata M 2020 Chapter 10 - Neutron radiation shielding composites for deep space exploration: An introduction *Micro and Nanostructured Composite Materials for Neutron Shielding Applications* Woodhead Publishing Series in Composites Science and Engineering ed Abdulrahman S T, Thomas S and Ahmad Z (Woodhead Publishing) pp 263–285 URL https://doi.org/10.1016/B978-0-12-819459-1.00010-6

[2] Pipich V, Dahdal Y, Rapaport H, Kasher R, Oren Y and Schwahn D 2013 **29** 7607–7617 URL https://doi.org/10.1021/la4001889

[3] Wei X, Zhao Q, Li X and Zhang T 2021 *JOM* **73**(3) 781–790 ISSN 1543-1851 URL https://doi.org/10.1007/s11837-020-04546-1

[4] Pylypchuk I V, Kovach V O, Iatsyshyn A V, Farrakhov O V, Bliznyuk V N and Kutsenko V O 2022 *IOP Conference Series: Earth and Environmental Science* **1049**(1) 012014 URL https://doi.org/10.1088/1755-1315/1049/1/012014

[5] Barth R F, Zhang Z and Liu T 2018 *Cancer Communications* **38**(1) 36 URL https://doi.org/10.1186/s40880-018-0280-5

[6] Was G S, Petti D, Ukai S and Zinkle S 2019 *Journal of Nuclear Materials* **527** 151837 URL https://doi.org/10.1016/j.jnucmat.2019.151837

[7] Kavetskiy A, Prior S, Torbert H and Yakubova G 2019 *Transactions* **121**(1) 539–541 URL https://doi.org/10.13182/T31237

[8] Dong M, Zhou S, Xue X, Feng X, Yang H, Sayyed M, Tishkevich D, Trukhanov A and Almousa N 2022 *Journal of Cleaner Production* **355** 131817 URL https://doi.org/10.1016/j.jclepro.2022.131817

[9] Kilicoglu O and Mehmetcik H 2021 *Radiation Physics and Chemistry* **189** 109721 URL https://doi.org/10.1016/j.radphyschem.2021.109721

[10] Elazaka A I, Zakaly H M H, Issa S A M, Rashad M, Tekin H O, Saudi H A, Gillette V H, Erguzel T T and Mostafa A G 2021 *Journal of Hazardous Materials* **403** 123738 URL https://doi.org/10.1016/j.jhazmat.2020.123738

[11] Baalamurugan J, Kumar V G, Chandrasekaran S, Balasundar S, Venkatraman B, Padmapriya R and Raja V K B 2021 *Composites Part B: Engineering* **216** 108885 URL https://doi.org/10.1016/j.compositesb.2021.108885

[12] Tyagi G, Singhal A, Routroy S, Bhunia D and Lahoti M 2021 *Journal of Hazardous Materials* **404** 124201 URL https://doi.org/10.1016/j.jhazmat.2020.124201

[13] Dong M, Xue X, Yang H, Liu D, Wang C and Li Z 2016 *Journal of Hazardous Materials* **318** 751–757 URL https://doi.org/10.1016/j.jhazmat.2016.06.012

[14] Jiang L T, Xu Z G, Fei Y K, Zhang Q, Qiao J and Wu G H 2019 *Composites Part B: Engineering* **168** 183–194 URL https://doi.org/10.1016/j.compositesb.2018.12.087

[15] Dilsiz K, Ogul H, Akman F, Agar O, Kacal M R, Polat H and İnan Dursun 2021 *Progress in Nuclear Energy* **139** 103865 URL https://doi.org/10.1016/j.pnucene.2021.103865

[16] Toyen D, Wimolmala E, Sombatsompop N, Markpin T and Saenboonruang K 2019 *Radiation Physics and Chemistry* **164** 108366 URL https://doi.org/10.1016/j.radphyschem.2019.108366

[17] Adeli R, Shirmardi S P and Ahmadi S J 2016 *Radiation Physics and Chemistry* **127** 140–146 URL https://doi.org/10.1016/j.radphyschem.2016.06.026

[18] Martin R F, D'cunha G, Pardee M and Allen B J 1989 *Pigment Cell Research* **2**(4) 330–332 URL https://doi.org/10.1111/j.1600-0749.1989.tb00213.x

[19] Martin R F, D'Cunha G, Pardee M and Allen B J 1988 *International Journal of Radiation Biology* **54**(2) 205–208 URL https://doi.org/10.1080/09553008814551641

[20] Goorley T and Nikjoo H 2000 *Radiation Research* **154**(5) 556–563 URL https://doi.org/10.1667/0033-7587(2000)154[0556:eapsft]2.0.co;2

[21] Japan Atomic Energy Agency, Nuclear Data Center 2020 Plotting Tool for ENDF (Evaluated Nuclear Data File) URL https://wwwndc.jaea.go.jp/ENDF_Graph/

[22] Abdulrahman S T, Thomas S and Ahmad Z (eds) 2020 *Micro and Nanostructured Composite Materials for Neutron Shielding Applications* Woodhead Publishing Series in Composites Science and Engineering (Woodhead Publishing) ISBN 978-0-12-819459-1 URL https://doi.org/10.1016/C2019-0-00001-5

[23] Tamayo P, Thomas C, Rico J, Cimentada A, Setién J and Polanco J A 2020 Chapter 2 - Review on neutron-

absorbing fillers *Micro and Nanostructured Composite Materials for Neutron Shielding Applications* Woodhead Publishing Series in Composites Science and Engineering ed Abdulrahman S T, Thomas S and Ahmad Z (Woodhead Publishing) pp 25–52 URL https://doi.org/10.1016/B978-0-12-819459-1.00002-7

[24] Birman A 2017 *LesPromInform* **4**(126) URL https://lesprominform.ru/jarticles.html?id=4714

[25] Baxter L, Herrman K, Panthi R, Mishra K, Singh R, Thibeault S, Benton E and Vaidyanathan R 2020 Chapter 3 - Thermoplastic micro- and nanocomposites for neutron shielding *Micro and Nanostructured Composite Materials for Neutron Shielding Applications* Woodhead Publishing Series in Composites Science and Engineering ed Abdulrahman S T, Thomas S and Ahmad Z (Woodhead Publishing) pp 53–82 URL https://doi.org/10.1016/B978-0-12-819459-1.00003-9

[26] Ramdani N 2020 Chapter 4 - Thermosetting micro- and nanocomposites for neutron radiation shielding *Micro and Nanostructured Composite Materials for Neutron Shielding Applications* Woodhead Publishing Series in Composites Science and Engineering ed Abdulrahman S T, Thomas S and Ahmad Z (Woodhead Publishing) pp 83–123 URL https://doi.org/10.1016/B978-0-12-819459-1.00004-0

[27] Kovach V, Iatsyshyn A, Pylypchuk I, Gurkovskyi V and Romanenko Y 2023 Analysis of Existing Types and Protection Methods Against Neutron Radiation from Different Sources *Systems, Decision and Control in Energy IV: Volume II. Nuclear and Environmental Safety* ed Zaporozhets A and Popov O (Cham: Springer Nature Switzerland) pp 77–89 URL https://doi.org/10.1007/978-3-031-22500-0_5

[28] Nuclear Energy Agency 2019 IAEA1437 SUPERMC 3.3.0. URL https://www.oecd-nea.org/tools/abstract/detail/iaea1437

[29] Hu C, Huang Q and Zhai Y 2021 *RSC Adv.* **11**(63) 40148–40158 URL https://doi.org/10.1039/D1RA07500D

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Selection of the optimal option for the transformation of the "Shelter" object into an environmentally safe system using the factor-criterion model of scenario analysis

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Abstract. The paper presents a comprehensive analysis of potential scenarios for Shelter Object transformation into an environmentally safe system after the commissioning of the New Safe Confinement. The analysis of scenarios is based on the developed factor-criteria model, which includes two groups of indicators in the scenario assessment: groups of factors and sets of criteria for each factor. The assessment of a separate scenario is carried out using the global value indicator. The global value of the scenario is determined taking into account the criterion content of all assessment factors. Characteristics of groups of factors and their criteria were determined by means of peer review. The assessment of the global values of scenarios allowed us to rank them. Based on the analysis, the most reasonable and realistic strategy for the phased removal/transfer to a controlled state of fuel-containing materials was proposed. The strategy also includes processes for further management of these materials and associated radioactive waste. As well as "Shelter" Object transformation processes in the process of its transformation into an environmentally safe system and determination of its final state. Based on the results of the comparative analysis of scenarios, it was found that the scenario that provides for the removal of known accumulations of fuel-containing materials during the life cycle of the New Safe Confinement is optimal if the activities on the phased retrieval of fuel-containing materials are properly financed.

1. Introduction

Despite the completion of construction and commissioning of the New Safe Confinement (NSC), the accumulation of fuel-containing materials (FCM) formed as a result of the beyond-design basis accident at Unit 4 remains the main source of hazard of the "Shelter" Object (SO). Moreover, the potential danger of FCM may increase over time due to the spontaneous destruction of the surface of paw-shaped FCM with the formation of highly active dust. The formation of such dust in the "Shelter" Object is a radio-ecological hazard not only of a local but also of a global nature since the NSC is not a hermetic structure. The problem of FCM degradation and methods of their evaluation and subsequent removal is extremely important not only for the SO but also for other facilities with similar conditions, such as the decommissioning of damaged reactors of the Fukushima Daiichi NPP [1]. Therefore, it is extremely important to remove or transfer to a controlled state FCM before the process of their destruction can acquire a large-scale character.

Resolution of the Presidium of the National Academy of Sciences of Ukraine No. 141 dated 16.05.2018 [2] states that scientific research on the transformation of the "Shelter" Object into an environmentally safe system is one of the priority areas of fundamental and applied research of specialized institutions of the National Academy of Sciences of Ukraine.

In work [3], the main directions of such research were determined and the following works were carried out:

- definition and analysis of factors affecting the choice of scenarios for the transformation of the "Shelter" Object;
- assessment of the risks of adverse effects on the environment of each of the FCM accumulations both during the life cycle of the NSC and after its decommissioning;
- analysis of possible options for the transformation of the "Shelter" Object;
- determination and substantiation of criteria for the final state of the "Shelter" Object;
- development of scenarios for the step-by-step transformation of the "Shelter" Object.

The ultimate goal of ensuring the nuclear and radiation safety of the "Shelter" Object – New Safe Containment" system (SO-NSC) should be the removal of all FCMs, and the organization of their safe storage and/or processing. An approach that considers the technological space of SO as a system of interconnected zones of FCM extraction, which are significantly different from each other, is promising. At the same time, for each extraction zone, one should consider individual technological approaches or scenarios for the extraction of FCM and handling of associated RAW.

At present [4], seven specific zones of FCM extraction in the future, using different technologies, are considered (figure 1):

- 1st zone – the central hall (CH), premises above the 18,000 mark, including the southern holding pool;
- 2nd zone – reactor shaft, sub-apparatus room (app. 305/2), etc. at marks from 9,000 to 18,000;
- 3rd zone – below the 9,000 mark: service corridor at the marks from minus 0.650 to 8.000, steam distribution corridor (SDC) (approx. 210/5, 210/6, 210/7), pressure-suppression pool (PSP):
  - second floor – PSP-2 (app. 012/13, 012/14, 012/15, 012/16);
  - first floor – PSP-1 (app. 012/5, 012/6, 012/7, 012/8);
- 4th zone – part of the hall within the SO;
- 5th zone – the space behind the pioneer walls;
- 6th zone – rubble under the cascade wall;
- 7th zone – local zone of the SO.

It is also necessary to take into account the guaranteed service life of the NSC, which is only 100 years, and the half-life periods of the nuclear materials contained in it are many orders of magnitude longer, and therefore their danger to the environment will remain for more than one millennium. This indicates that the problem of further transformation of the "Shelter" Object into an environmentally safe system (ESS) remains relevant even after the commissioning of the NSC and requires special scientific research.

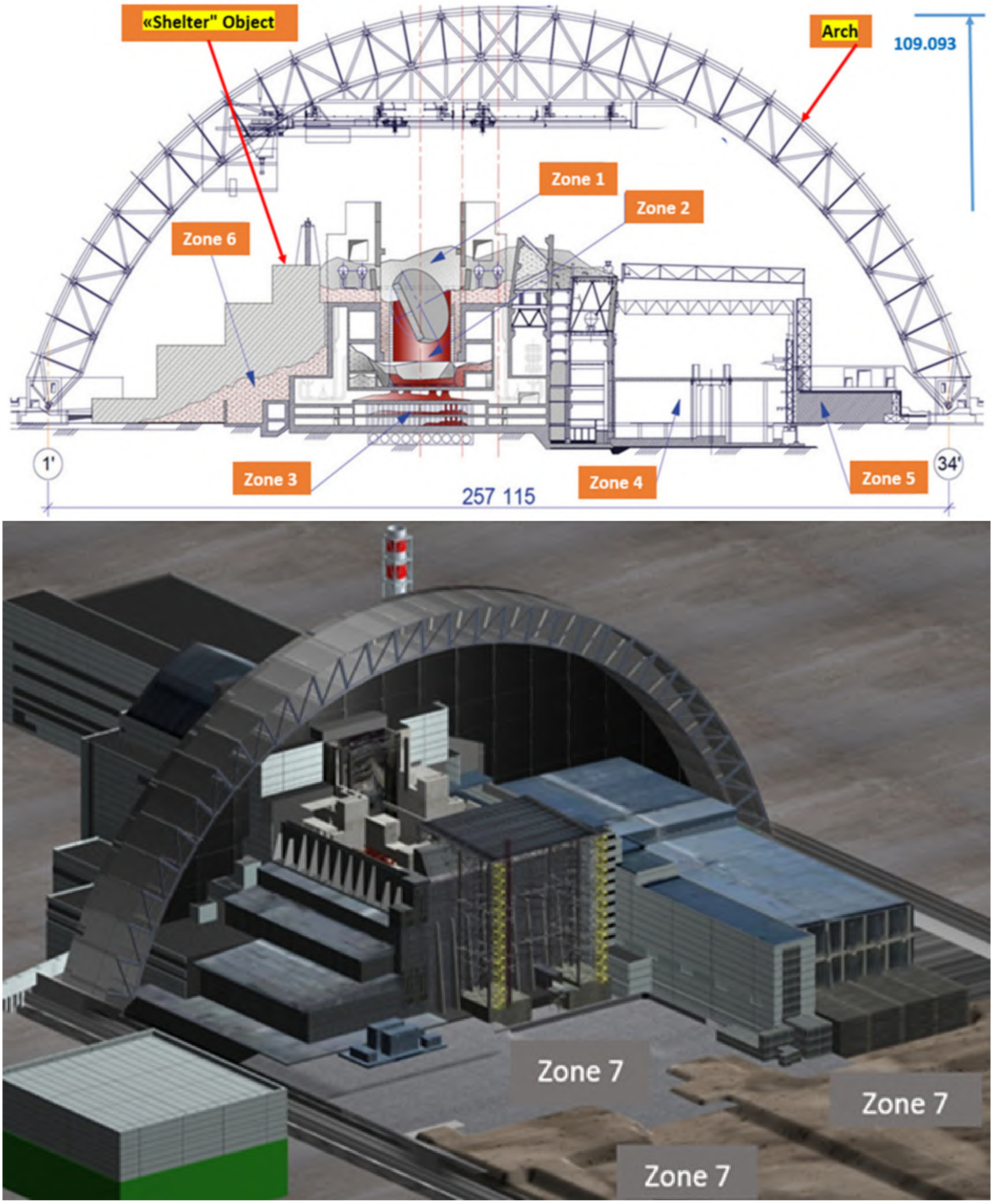

Figure 1. FCM extraction zones. Zone 1 – upper marks of the SO (Central Hall and other rooms are above the mark 18,000); Zone 2 – intermediate grades of SO (utility room, other rooms on the marks from 9,000 to 18,000); Zone 3 – lower marks of SO (premises below the mark 9,000); Zone 4 – part of the Machinery Hall within the SO; Zone 5 – the space behind the Pioneer walls; Zone 6 – rubble under the cascading wall; Zone 7 – local zone of the SO.

Thus, as of 2022, the following scenarios for the transformation of the “Shelter” Object into an environmentally safe system [5] have been determined, presented in table 1.

Table 1. Potential scenarios for the implementation of the strategy “staged removal of FCM”.

No	Withdrawal during the life cycle of the NSC	Deferred withdrawal after decommissioning of the NSC	Burial on site
1	Zones 1-6	Zone 7	–
2	Zones 1, 2, 3, 4, 6	Zones 5, 7	–
3	Zones 1, 2, 3, 4, 6	Zone 5	Zone 7
4	Zones 1, 2, 3 (SDC), 4, 6	Zones 3 (PSP), 5	Zone 7
5	Zones 1, 2, 3 (SDC), 4	Zones 3 (PSP), 5, 6	Zone 7
6	Zones 1, 2, 3 (SDC)	Zones 3 (PSP), 4, 5, 6	Zone 7
7	Zones 1, 2, 3 (SDC)	Zones 3 (PSP), 5, 6	Zones 4, 7
8	Zones 1, 2, 3 (SDC)	Zones 3 (PSP), 6	Zones 4, 5, 7
9	Zones 1, 2	Zone 3	Zones 4, 5, 6, 7
10	Zones 1, 2	Zone 3 (SDC)	Zones 3 (PSP), 4, 5, 6, 7

The object of the study is the SO-NSC system. The research object is a complex system in which its technical, technological, security, financial, infrastructural, and other parameters are connected. Therefore, the main method of his research is a systematic analysis of factors affecting the solution of the problems of transforming the “Shelter” Object into an environmentally safe system.

The subject of the research is a comprehensive analysis of the scenarios of transformation of the “Shelter” Object into an environmentally safe system. The complexity of the analysis processes is ensured by taking into account all the parametric and non-parametric component characteristics of the scenarios, as well as their internal technical, economic, safety, technological, etc. structure.

In work [6], a methodology for detailed assessment of nuclear power systems (NPS) was developed, including key assessment areas: economy, infrastructure, waste management, proliferation, resistance to proliferation, environment, etc. Comprehensive decision-making support is necessary for the comparative evaluation of alternative options and the selection of the most promising solution. But estimates according to the INPRO methodology [7] require sufficiently detailed design information for NPS components. For the SO-NSC system, such information is at the stage of development. The most adequate use of the multi-criteria optimization technique for the comparative evaluation of the scenarios of the transformation of the “Shelter” Object into an environmentally safe system is the work [8], using which it was decided to apply the expert evaluation of the criteria that characterize the scenarios.

The main tasks of the research presented in the work are:

- complex analysis of scenarios based on the grouping of factors and the determination of criteria relevant to them;
- the creation of a comprehensive evaluation model based on the global value of the scenario;
- practical use of the scenario evaluation model based on collegial expert evaluation of factors and criteria for the studied scenarios.

The article aims to rank the scenarios by their global (complex) value. A comprehensive analysis of the scenarios of step-by-step extraction of FCM after the commissioning of the NSC is being carried out for the first time.

2. Model of complex analysis of scenarios of transformation of the "Shelter" Object

2.1. Formation of a data array for complex analysis of scenarios

According to the recommendations of the IAEA [9–12], the decision-making criteria include:

- radiation protection criteria, which are:
  - implementation of anti-radiation protection of personnel, the population, and the environment in accordance with the requirements of the Laws, norms, and rules in force in Ukraine;
  - implementation of anti-radiation protection of personnel in accordance with the ALARA principle [13];
  - assessment of radiation consequences for personnel, which takes into account exposure caused both by activities during the implementation of the main task and by being in the exclusion zone;
  - assessment of radiation consequences of potential accidents for personnel, population, and environment;
- criteria for handling RAW;
- general technical criteria, which are:
  - creation of deep echelon defense;
  - quality assurance;
  - exchange of experience;
  - consideration of the human factor;
  - application of proven engineering and technical practice.

For the practical application and implementation of the environmental safety analysis of work execution options in the implementation of scenarios of phased removal of FCM, the criteria given in table 2 are defined.

The comparative analysis of the proposed scenarios for the phased removal of FCM is performed based on expert evaluations of the values of an array of criteria, which reflect various aspects of the condition of the "Shelter" Object and the specifics of its transformation into an environmentally safe system. The key goal in determining expert evaluations is the indicator of "achieving a given level of environmental safety". A nine-point scale is proposed for expert evaluation of criteria [14].

All the specified criteria are evaluated non-parametrically by a group of experts (in points), collegially, with the definition of a jointly agreed point evaluation of the criteria for each scenario.

2.2. Formalization of the model of the comparative analysis of scenarios of the conversion of SO

The array of criteria presented in table 2 can be grouped by factorial features, namely:

- factor 1 – security components of scenarios:
  - risks of changes in properties (degradation) of FCM over time R_D, %;
  - risks of destruction of protective barriers around FCM accumulations over time R_{DPB}, %;
  - radiological risks R_{Rad}, person/year;
  - project implementation time (scenario) T, years;
- factor 2 – financial components of the scenarios:
  - costs for creating protective barriers for containment and isolation of FCM after decommissioning NSC OE_{CPB}, thousand UAH;

Table 2. Criteria for the comparative analysis of scenarios of phased extraction of FCM.

No	The name of the criterion	Marking
1	Operating costs for ensuring the current security of the "Shelter" Object, thousand UAH.	OE_{ECS}
2	Costs for the creation of protective barriers for containment and isolation of FCM after decommissioning of the NSC, thousand UAH.	OE_{CPB}
3	Costs for the creation of additional infrastructure for the extraction and further handling of FCM and other RAW after the decommissioning of the NSC, thousand UAH.	OE_{CAI}
4	The degree of use of the infrastructure of the NSC for the extraction and further handling of FCM and other RAW, %	L_{UI}
5	Risks of unpreparedness of warehouses for intermediate storage of recovered FCM, %	R_{UISF}
6	Risks of the unpreparedness of the geological repository for the final disposal of FCM, %	R_{UGR}
7	Radiological risks, people/year	R_{Rad}
8	Risks of changes in properties (degradation) of FCM over time, %	R_D
9	Risks of underfunding of works on the phased removal of FCM and their subsequent handling, thousand UAH/year	R_{UFW}
10	Risks of the destruction of protective barriers around FCM accumulations over time, %	R_{DPB}
11	Project implementation time (scenario), years	T

  – costs for the creation of additional infrastructure for the removal and further handling of FCM and other RAW after the decommissioning of the NSC OE_{CAI}, thousand UAH;
  – operational costs for ensuring the current security of the OE_{ECS} "Shelter" Object, thousand UAH;
  – risks of underfunding of works on the phased removal of FCM and their further handling by R_{UFW}, thousand UAH / year;
- factor 3 – infrastructural components of the scenarios:
  – the degree of use of the infrastructure of the NSC for the extraction and further handling of FCM and other RAW, L_{UI}, %;
  – risks of non-readiness of storage facilities for intermediate storage of recovered FCM R_{UISF}, %;
  – risks of unpreparedness of the geological repository for the final disposal of the FCM R_{UGR}, %;

By analogy with [15], we will introduce the concept of "scenario values" SF_i, (significance function). For practical use in accordance with the purpose and objectives of the research, this indicator is identically equal to the predicted level of environmental safety in the implementation of the i-th scenario with the corresponding groups of factors Φ_i and their constituent criteria:

$$\begin{Bmatrix} SF_1 \\ ... \\ SF_p \end{Bmatrix} \equiv \begin{pmatrix} \Phi_1 \begin{Bmatrix} R_{D,1} & R_{DPB,1} & R_{Rad,1} & T_1 \\ ... & ... & ... & ... \\ R_{D,p} & R_{DPB,p} & R_{Rad,p} & T_p \end{Bmatrix} \\ \Phi_2 \begin{Bmatrix} OE_{ECS,1} & OE_{CPB,1} & OE_{CAI,1} & R_{UFW,1} \\ ... & ... & ... & ... \\ OE_{ECS,p} & OE_{CPB,p} & OE_{CAI,p} & R_{UFW,p} \end{Bmatrix} \\ \Phi_3 \begin{Bmatrix} L_{UI,1} & R_{UISF,1} & R_{UGR,1} \\ ... & ... & ... \\ L_{UI,p} & R_{UISF,p} & R_{UGR,p} \end{Bmatrix} \end{pmatrix} \quad (1)$$

where:

- $\Phi_1 \begin{Bmatrix} R_{D,1} & R_{DPB,1} & R_{Rad,1} & T_1 \\ ... & ... & ... & ... \\ R_{D,p} & R_{DPB,p} & R_{Rad,p} & T_p \end{Bmatrix}$ – safety factor of scenarios with its own criteria;
- $\Phi_2 \begin{Bmatrix} OE_{ECS,1} & OE_{CPB,1} & OE_{CAI,1} & R_{UFW,1} \\ ... & ... & ... & ... \\ OE_{ECS,p} & OE_{CPB,p} & OE_{CAI,p} & R_{UFW,p} \end{Bmatrix}$ – the financial factor of the scenarios with its criteria;
- $\Phi_3 \begin{Bmatrix} L_{UI,1} & R_{UISF,1} & R_{UGR,1} \\ ... & ... & ... \\ L_{UI,p} & R_{UISF,p} & R_{UGR,p} \end{Bmatrix}$ – the infrastructural factor of the scenarios with its criteria.

Thus, the initial conditions for using the scenario evaluation method based on collective expert evaluations are a set of factors Φ_1, Φ_2 and Φ_3 with groups of criteria defined for them.

Then a separate i-th scenario will be represented by a complex or integral value criterion W_i, which is determined based on the weight of factors and criteria that form them. This will allow you to rank the scenarios according to their relative value:

$$W^* > ... > W^0 \quad (2)$$

where $W_i^* = \text{argmax}(W_i), W_i^0 = \text{argmin}(W_i)$.

2.3. Algorithm for determining complex values of scenarios based on group expert evaluation

Determining the complex values of scenarios based on group expert evaluation is a step-by-step process.

At stage 1, arrays of scenario evaluation criteria are formed

$$\begin{gathered} Sc_i = (OE_{ECS(i)}, OE_{CPB(i)}, OE_{CAI(i)}, L_{UI(i)}, \\ R_{UISF(i)}, R_{UGR(i)}, R_{Rad(i)}, R_{D(i)}, R_{UFW(i)}, R_{DPB(i)}, T_i) \end{gathered} \quad (3)$$

where: i is a separate scenario, $i = \overline{1,p}$, p is the number of scenarios.

As a result, we get an array of criteria with a definition of their characteristics.

At stage 2, criteria are grouped by qualitatively homogeneous factors Φ_j.

The result is the formation of three groups of factors for p scenarios with their own criteria (1): Φ_1 – security, Φ_2 – financial, Φ_3 – infrastructural.

Sc_1	...	Sc_i	...	Sc_p
Φ_{11}	...	Φ_{i1}	...	Φ_{p1}
Φ_{12}	...	Φ_{i2}	...	Φ_{p2}
Φ_{13}	...	Φ_{i3}	...	Φ_{p3}

At stage 3, a group expert evaluation of factors and criteria within the factors is carried out according to point evaluations according to the proposed scale.

The result is the formation of point scores expert assessment matrices for factors and their criteria for p scenarios:

Scenario 1		...	Scenario i		...	Scenario p	
factors (points)	criteria (points)	...	factors (points)	criteria (points)	...	factors (points)	criteria (points)
Φ_{11}	$R_{D(1)}$, $R_{DPB(1)}$, $R_{Rad(1)}$, T_1	...	Φ_{i1}	$R_{D(i)}$, $R_{DPB(i)}$, $R_{Rad(i)}$, T_i	...	Φ_{p1}	$R_{D(p)}$, $R_{DPB(p)}$, $R_{Rad(p)}$, T_p
Φ_{12}	$OE_{ECS(1)}$, $OE_{DPB(1)}$, $OE_{CAI(1)}$, $R_{UFW(1)}$	...	Φ_{i2}	$OE_{ECS(i)}$, $OE_{DPB(i)}$, $OE_{CAI(i)}$, $R_{UFW(i)}$	...	Φ_{p2}	$OE_{ECS(p)}$, $OE_{DPB(p)}$, $OE_{CAI(p)}$, $R_{UFW(p)}$
Φ_{13}	$L_{UI(1)}$, $R_{UISF(1)}$, $R_{UGR(1)}$	...	Φ_{i3}	$L_{UI(i)}$, $R_{UISF(i)}$, $R_{UGR(i)}$	...	Φ_{p3}	$L_{UI(p)}$, $R_{UISF(p)}$, $R_{UGR(p)}$

At stage 4, the matrix of advantages for factors is formed based on the factor scores:

$$A^{\Phi} = (a_{i,j}^{\Phi}) \tag{4}$$

where: $a_{i,j}^{\Phi}$ – advantage of the i-th factor over the j-th. For the i-th scenario, the benefits matrix looks like this:

$$A_i^{\Phi} = \begin{pmatrix} 1 & \Phi_{i1}/\Phi_{i2} & \Phi_{i1}/\Phi_{i3} \\ \Phi_{i2}/\Phi_{i1} & 1 & \Phi_{i2}/\Phi_{i3} \\ \Phi_{i3}/\Phi_{i1} & \Phi_{i3}/\Phi_{i2} & 1 \end{pmatrix} \tag{5}$$

The result is an estimate of the weight of the factors for the i-th scenario according to the formulas:

$$\Omega_i^{\Phi 1} = \frac{\sqrt[3]{1 \cdot (\frac{\Phi_{i1}}{\Phi_{i2}}) \cdot (\frac{\Phi_{i1}}{\Phi_{i3}})}}{\sqrt[3]{1 \cdot (\frac{\Phi_{i1}}{\Phi_{i2}}) \cdot (\frac{\Phi_{i1}}{\Phi_{i3}})} + \sqrt[3]{(\frac{\Phi_{i2}}{\Phi_{i1}}) \cdot 1 \cdot (\frac{\Phi_{i2}}{\Phi_{i3}})} + \sqrt[3]{(\frac{\Phi_{i3}}{\Phi_{i1}}) \cdot (\frac{\Phi_{i3}}{\Phi_{i2}}) \cdot 1}} \tag{6}$$

$$\Omega_i^{\Phi 2} = \frac{\sqrt[3]{(\frac{\Phi_{i2}}{\Phi_{i1}}) \cdot 1 \cdot (\frac{\Phi_{i2}}{\Phi_{i3}})}}{\sqrt[3]{1 \cdot (\frac{\Phi_{i1}}{\Phi_{i2}}) \cdot (\frac{\Phi_{i1}}{\Phi_{i3}})} + \sqrt[3]{(\frac{\Phi_{i2}}{\Phi_{i1}}) \cdot 1 \cdot (\frac{\Phi_{i2}}{\Phi_{i3}})} + \sqrt[3]{(\frac{\Phi_{i3}}{\Phi_{i1}}) \cdot (\frac{\Phi_{i3}}{\Phi_{i2}}) \cdot 1}} \tag{7}$$

$$\Omega_i^{\Phi 3} = \frac{\sqrt[3]{(\frac{\Phi_{i3}}{\Phi_{i1}}) \cdot (\frac{\Phi_{i3}}{\Phi_{i2}}) \cdot 1}}{\sqrt[3]{1 \cdot (\frac{\Phi_{i1}}{\Phi_{i2}}) \cdot (\frac{\Phi_{i1}}{\Phi_{i3}})} + \sqrt[3]{(\frac{\Phi_{i2}}{\Phi_{i1}}) \cdot 1 \cdot (\frac{\Phi_{i2}}{\Phi_{i3}})} + \sqrt[3]{(\frac{\Phi_{i3}}{\Phi_{i1}}) \cdot (\frac{\Phi_{i3}}{\Phi_{i2}}) \cdot 1}} \tag{8}$$

At stage 5, a preference matrix is formed for criteria based on point scores:

$$A^{KP} = (a_{i,j}^{KP}) \tag{9}$$

where: $a_{i,j}^{KP}$ – advantage of the i-th criterion over the j-th. For the i-th scenario, the benefits matrix looks like this:

- for the array of criteria grouped in "Factor 1 – security components of scenarios"

$$A_i^{KP}(\Phi_1) = \begin{pmatrix} 1 & R_{D(i)}/R_{DBP(i)} & R_{D(i)}/R_{Rad(i)} & R_{D(i)}/T_{(i)} \\ R_{DBP(i)}/R_{D(i)} & 1 & R_{DBP(i)}/R_{Rad(i)} & R_{DBP(i)}/T_(i) \\ R_{Rad(i)}/R_{D(i)} & R_{Rad(i)}/R_{DBP(i)} & 1 & R_{Rad(i)}/T_(i) \\ T_{(i)}/R_{D(i)} & T_{(i)}/R_{DBP(i)} & T_(i)/R_{Rad(i)} & 1 \end{pmatrix} \quad (10)$$

- for the array of criteria grouped in "Factor 2 – financial criteria of scenarios"

$$A_i^{KP}(\Phi_2) = \begin{pmatrix} 1 & OE_{ECS(i)}/OE_{CPB(i)} & OE_{ECS(i)}/OE_{CAI(i)} & OE_{ECS(i)}/R_{UFW(i)} \\ OE_{CPB(i)}/OE_{ECS(i)} & 1 & OE_{CPB(i)}/OE_{CAI(i)} & OE_{CPB(i)}/R_{UFW(i)} \\ OE_{CAI(i)}/OE_{ECS(i)} & OE_{CAI(i)}/OE_{CPB(i)} & 1 & OE_{CAI(i)}/R_{UFW(i)} \\ R_{UFW(i)}/OE_{ECS(i)} & R_{UFW(i)}/OE_{CPB(i)} & R_{UFW(i)}/OE_{CAI(i)} & 1 \end{pmatrix} \quad (11)$$

- for the array of criteria grouped in "Factor 3 – infrastructural criteria of scenarios"

$$A_i^{KP}(\Phi_3) = \begin{pmatrix} 1 & L_{UI(i)}/R_{UISF(i)} & L_{UI(i)}/R_{UGR(i)} \\ R_{UISF(i)}/L_{UI(i)} & 1 & R_{UISF(i)}/R_{UGR(i)} \\ R_{UISF(i)}/L_{UI(i)} & R_{UGR(i)}/R_{UISF(i)} & 1 \end{pmatrix} \quad (12)$$

The result is an assessment of the weight of the criteria for the relevant factors for the i-th scenario as a ratio of the geometric mean from a separate row of the matrices (9), (10), (11) to the sum of the geometric means of all rows of the matrices:

$$W_i^{\Phi 1,2,3} = \frac{\sqrt[m]{a_{ij} \cdot \ldots \cdot a_{im}}}{\sum \sqrt[m]{a_{ij} \cdot \ldots \cdot a_{im}}} \quad (13)$$

where: m – the number of criteria in the corresponding factor.

For the specified factors, we will obtain the vectors of the relative values of the criteria:

$$W_i^{\Phi 1} = \begin{pmatrix} W_{R_{D(i)}} \\ W_{R_{DPB(i)}} \\ W_{R_{Rad(i)}} \\ W_{T_{(i)}} \end{pmatrix}, W_i^{\Phi 2} = \begin{pmatrix} W_{OE_{ECS(i)}} \\ W_{OE_{CPB(i)}} \\ W_{OE_{CAI(i)}} \\ W_{R_{UFW(i)}} \end{pmatrix}, W_i^{\Phi 3} = \begin{pmatrix} W_{L_{UI(i)}} \\ W_{R_{UISF(i)}} \\ W_{R_{UGR(i)}} \end{pmatrix} \quad (14)$$

At stage 6, a vector of complex indicators $W(\Omega, \omega)$ is formed, containing evaluations of the criteria that form them $\omega_1^i, , \omega_k^i$ and groups of factors based on determining their weights $\{\Omega^1, , \Omega^m\}$:

$$W = [\langle(\omega_1^1, ..., \omega_k^1), \Omega^1\rangle; \langle(\omega_1^2, ..., \omega_l^1)\Omega^2\rangle; ...; \langle(\omega_1^m, ..., \omega_z^m)\Omega^j\rangle] \quad (15)$$

where: k, l, z – the number of criteria that form the relevant factor.

The result is the determination of the complex indicators of the weight (values) of the scenarios $W = \langle\omega, \Omega\rangle$ taking into account the determination of the weight of the relevant criteria ω based on the weight of the structural factors Ω. It is performed using a geometric weighted multiplicative convolution of the form:

$$W_{(Sc_j)} = \sqrt[m]{\Pi_{i=1}^m [(\omega_i^j)^{\Omega^j}]_{(Sc_j)}}, j = \overline{1, n} \quad (16)$$

where: $S_{Cj} \in S_c$ – the array of scripts; ω_i^j – weights of the criteria that form the factors of the corresponding scenarios; Ω^j – factor weights for scenarios.

For expression (15), we obtain the vectors of the relative values of the scenarios defined by (16):

$$W = \begin{pmatrix} W_{Sc(1)} \\ \ldots \\ W_{Sc(i)} \\ \ldots \\ W_{Sc(p)} \end{pmatrix} \tag{17}$$

Scenarios are ranked by the value of their complex value according to (2):

$$W^* > \ldots > W^0$$

where: $W_i^* = \text{argmax}(W_i), W_i^0 = \text{argmin}(W_i)$.

3. Practical implementation of a comparative analysis of scenarios for the transformation of the "Shelter" Object into an environmentally safe system

According to clause 1 of the article, the comparative analysis of scenarios will be carried out on the basis of factorial-criterion group expert evaluation (EE). A working group of experts was created to perform the work according to the EE method, which meets the requirements of qualification and competence, which will ensure the reliability of the implementation of the EE. In the work of the group of experts on scenario evaluation, collective expert evaluations are applied. The input conditions for EE scenarios are:

- number of scenarios – 10;
- all expert assessments for all stages of practical use of the model are carried out on a nine-point scale (from 1 to 9 points).

Each factor or criterion within the scenario is assigned a collegial assessment in points, which can be equivalent for different indicators and different scenarios. The process of collegial point expert evaluation is carried out in two stages:

- stage 1 – scoring of three groups of FACTORS for ten scenarios;
- stage 2 – scoring of the CRITERIA, which are included in the relevant groups of factors, for ten scenarios.

Based on the results of expert scoring for ten scenarios, the relative complex values of the scenarios are determined according to the proposed model. Based on the determined relative complex values of the scenarios, the scenarios are ranked according to their relative complex value.

At the **first stage** of the model implementation, a group expert evaluation of defined groups of scenario factors was carried out. The results of a collegial group expert survey and evaluation of factor weights for the scenarios calculated according to formulas (6), (7) and (8) are given in table 3.

At the **second stage** of the model implementation, a group expert evaluation of the criteria for the relevant groups of scenario factors was performed. The results of the collegial group expert survey are given in tables 4-6.

The determination of the complex indicators of the values of the scenarios taking into account the determination of the weight of the relevant criteria based on the weight of the structural factors of the type (15) was carried out according to the formula (16).

The results of the comprehensive assessment of the scenarios can be provided either in the form of a vector or in a tabular format. T7 presents the results of calculations in tabular format.

Table 3. Results of group expert assessment of scenario factors.

Scenario	Scenario factors (in points from 1 to 9)			Factor weights for scenarios		
	$\Phi 1$	$\Phi 2$	$\Phi 3$	$\Omega(\Phi 1)$	$\Omega(\Phi 2)$	$\Omega(\Phi 3)$
Scenario 1	9	7	9	0.360	0.280	0.360
Scenario 2	9	7	8	0.375	0.292	0.333
Scenario 3	8	6	8	0.364	0.273	0.364
Scenario 4	8	6	8	0.364	0.273	0.364
Scenario 5	7	6	7	0.350	0.300	0.350
Scenario 6	7	5	7	0.368	0.263	0.368
Scenario 7	6	5	6	0.353	0.294	0.353
Scenario 8	5	6	6	0.294	0.353	0.353
Scenario 9	4	7	5	0.250	0.438	0.313
Scenario 10	4	7	5	0.250	0.438	0.313

Table 4. Group expert evaluation of criteria for groups of scenario factors (safety factor).

Safety factors (in points from 1 to 9)					Scenario criteria values			
Scenario	R_D	R_{DPB}	R_{Rad}	T	$\omega(R_D)$	$\omega(R_{DPB})$	$\omega(R_{Rad})$	$\omega(T)$
Scenario 1	9	9	8	9	0.257	0.257	0.229	0.257
Scenario 2	9	9	8	7	0.273	0.273	0.242	0.212
Scenario 3	8	8	8	8	0.250	0.250	0.250	0.250
Scenario 4	7	8	7	7	0.241	0.276	0.241	0.241
Scenario 5	6	8	7	6	0.222	0.296	0.259	0.222
Scenario 6	6	8	7	5	0.231	0.308	0.269	0.192
Scenario 7	6	8	6	7	0.222	0.296	0.222	0.259
Scenario 8	6	8	6	8	0.214	0.286	0.214	0.286
Scenario 9	5	8	5	9	0.185	0.296	0.185	0.333
Scenario 10	5	7	5	9	0.192	0.269	0.192	0.346

The vector of complex relative values of the scenarios defined by (16):

$$W = \begin{pmatrix} W_{Sc(1)} = 0.6642 \\ W_{Sc(2)} = 0.6212 \\ W_{Sc(3)} = 0.6369 \\ W_{Sc(4)} = 0.6382 \\ W_{Sc(5)} = 0.6429 \\ W_{Sc(6)} = 0.6453 \\ W_{Sc(7)} = 0.6461 \\ W_{Sc(8)} = 0.6449 \\ W_{Sc(9)} = 0.6333 \\ W_{Sc(10)} = 0.6328 \end{pmatrix} \tag{18}$$

The results of the ranking of the scenarios by the value of the complex value:

$W_i^* = \text{argmax}(W_i) = 0.6642 - \text{scenario 1}$

$W_i^{-1} = 0.6461 - \text{scenario 7}$

Table 5. Group expert evaluation of criteria for groups of scenario factors (financial factor).

Financial factors (in points from 1 to 9)					Scenario criteria values			
Scenario	OE_{CPB}	OE_{CAI}	OE_{ECS}	R_{UFW}	$\omega(OE_{CPB})$	$\omega(OE_{CAI})$	$\omega(OE_{ECS})$	$\omega(R_{UFW})$
Scenario 1	9	8	7	3	0.333	0.296	0.259	0.111
Scenario 2	9	8	7	3	0.333	0.296	0.259	0.111
Scenario 3	8	8	7	4	0.296	0.296	0.259	0.148
Scenario 4	8	7	6	4	0.320	0.280	0.240	0.160
Scenario 5	8	6	6	5	0.320	0.240	0.240	0.200
Scenario 6	7	5	5	6	0.304	0.217	0.217	0.261
Scenario 7	6	6	4	7	0.261	0.261	0.174	0.304
Scenario 8	6	6	4	8	0.250	0.250	0.167	0.333
Scenario 9	5	5	3	9	0.227	0.227	0.136	0.409
Scenario 10	5	5	3	9	0.227	0.227	0.136	0.409

Table 6. Group expert assessment of criteria for groups of scenario factors (infrastructure factor).

Infrastructure factors (in points from 1 to 9)				Scenario criteria values		
Scenario	L_{UI}	P_{UISF}	P_{UGR}	$\omega(L_{UI})$	$\omega(P_{UISF})$	$\omega(P_{UGR})$
Scenario 1	9	5	1	0.600	0.333	0.067
Scenario 2	9	5	1	0.600	0.333	0.067
Scenario 3	9	7	2	0.500	0.389	0.111
Scenario 4	8	7	2	0.471	0.412	0.118
Scenario 5	7	7	3	0.412	0.412	0.176
Scenario 6	6	7	3	0.375	0.438	0.188
Scenario 7	6	8	5	0.316	0.421	0.263
Scenario 8	6	8	5	0.316	0.421	0.263
Scenario 9	6	9	7	0.273	0.409	0.318
Scenario 10	5	9	7	0.238	0.429	0.333

Table 7. Complex factorial and criterion evaluation of scenarios.

Scenario	Complex value of the scenario, W
Scenario 1	0.664214
Scenario 2	0.621247
Scenario 3	0.636855
Scenario 4	0.638161
Scenario 5	0.642854
Scenario 6	0.645337
Scenario 7	0.646057
Scenario 8	0.644912
Scenario 9	0.633337
Scenario 10	0.632818

$$\begin{gathered}
W_i^{-2} = 0.6453 - \text{scenario } 6 \\
W_i^{-3} = 0.6449 - \text{scenario } 8 \\
W_i^{-4} = 0.6429 - \text{scenario } 5 \\
W_i^{-5} = 0.6382 - \text{scenario } 4 \\
W_i^{-6} = 0.6369 - \text{scenario } 3 \\
W_i^{-7} = 0.6333 - \text{scenario } 9 \\
W_i^{-8} = 0.6328 - \text{scenario } 10 \\
W_i^{0} = \operatorname{argmin}(W_i) = 0.6212 - \text{scenario } 2
\end{gathered}$$

4. Conclusions

Thus, on the basis of the conducted research, the following conclusions can be drawn:

- collegial expert assessments conducted for factors and their criteria are competent and consistent;
- calculated based on EE weights of the factors $\Omega_i^{\Phi j}$ for the considered scenarios and the weights of the criteria ω_i^j for the corresponding Ω^j factors for the scenarios based on the comparison matrices are reliable and significant which is confirmed by the calculated consistency indices that do not exceed 10%;
- the vector of relative complex values of scenarios (15) is the basis for making managerial decisions;
- according to the $\operatorname{argmax}(W_i)$ principle the best scenario is "scenario 1" – the base scenario. The value of the relative complex value is $W_i^* = \operatorname{argmax}(W_i) = 0.6642$;
- the worst scenario according to the $\operatorname{argmin}(W_i)$ principle is "scenario 2". The value of the relative complex value of which is the minimum among the estimates and is $W_i^0 = \operatorname{argmin}(W_i) = 0.6212$;
- a series of scenario evaluations ranked by relative complex value:

$$\begin{cases} W_i^* = W_1 > W_7 > W_6 > W_8 > W_5 > W_4 > W_3 > W_9 > W_i^0 = W_10 \\ 0.6642 > 0.6461 > 0.6453 > 0.6449 > 0.6429 > 0.6382 > 0.6369 > 0.6333 > 0.6328 > 0.621 \end{cases}$$

Therefore, with proper financing of the step-by-step extraction of FCM, the priority is the basic scenario – Scenario 1, which provides for the removal of all FCM accumulations (except FCM localized in man-made soil under NSC structures) during the life cycle of NSC. When implementing such a scenario, the NSC infrastructure is used to the maximum, the costs of creating protective barriers to contain and isolate FCM are reduced, as well as the costs of creating additional infrastructure for the extraction and further handling of FCM and other RAW after decommissioning of the NSC.

Since the values of the values of the relative complex value of all scenarios do not differ significantly, under certain circumstances (mostly due to the financial component) other scenarios, which provide for the delayed removal of individual accumulations of FCM, may become better.

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References

[1] Kitagaki T, Krasnov V A and Ikeda-Ohno A 2023 *Journal of Nuclear Materials* **576** 154224 ISSN 0022-3115 URL https://doi.org/10.1016/j.jnucmat.2022.154224

[2] Presidium of the National Academy of Sciences of Ukraine 2018 Resolution No. 141

[3] 2021 Comprehensive analysis of potential scenarios for the transformation of the "Shelter" object into an environmentally safe system after the commissioning of a new safe confinement Interim report

[4] Stelmakh D A, Svyerchkov S F, Shumilova L E and Dyldin V Y 2016 *Problemy bezpeky atomnykh elektrostantsii i Chornobylia* **27** 35–42 URL http://nbuv.gov.ua/UJRN/Pbaech_2016_27_7

[5] 2022 Comprehensive analysis of potential scenarios for the transformation of the "Shelter" object into an environmentally safe system after the commissioning of a new safe confinement Interim report

[6] 2019 *Application of Multi-criteria Decision Analysis Methods to Comparative Evaluation of Nuclear Energy System Options: Final Report of the INPRO Collaborative Project KIND* (*Nuclear Energy Series* no NG-T-3.20) (Vienna: International Atomic Energy Agency) ISBN 978-92-0-102319-3 URL https://tinyurl.com/2s3wy3j6

[7] 2010 *Introduction to the Use of the INPRO Methodology in a Nuclear Energy System Assessment* (*Nuclear Energy Series* no NP-T-1.12) (Vienna: International Atomic Energy Agency) ISBN 978-92-0-110410-6 URL https://www.iaea.org/publications/8591/introduction-to-the-use-of-the-inpro-methodology-in-a-nuclear-energy-system-assessment

[8] Derengovskiy V V and Nosovskiy A V 2018 *Nuclear Physics and Atomic Energy* **19**(2) 166–172 URL https://doi.org/10.15407/jnpae2018.02.166

[9] ICRP 1983 *Cost-Benefit Analysis in the Optimization of Radiation Protection* (*ICRP Publication* no 37) (Pergamon Press) URL https://www.icrp.org/publication.asp?id=ICRP%20Publication%2037

[10] ICRP 1990 *Optimization and Decision Making in Radiological Protection* (*ICRP Publication* no 55) (Pergamon Press) URL https://www.icrp.org/publication.asp?id=ICRP%20Publication%2055

[11] ICRP 1977 *Recommendations of the ICRP* (*ICRP Publication* no 26) (Pergamon Press) URL https://www.icrp.org/publication.asp?id=ICRP%20Publication%2026

[12] 1994 Dose Control at Nuclear Power Plants Report 120 National Council on Radiation Protection and Measurements Bethesda, MD URL https://ncrponline.org/shop/reports/report-no-120-dose-control-at-nuclear-power-plants-1994/

[13] Lochard J, Lombard J, Stokell P J and Croft J R 1991 Alara - from theory towards practice Tech. Rep. EUR–13796 Commission of the European Communities Luxembourg

[14] Saaty T 1980 *The Analytic Hierarchy Process: Planning, Priority Setting, Resource Allocation* (New York: McGraw-Hill)

[15] Derenhovskyi V V and Skiter I S 2022 *Nuclear Power and the Environment* (1(23)) 45–55 ISSN 2311-8253 URL https://doi.org/10.31717/2311-8253.22.1.5

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The formation of the carbonate system of circulating cooling water of the Rivne NPP and its influence on changes in the surface waters pH levels of the Styr river

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Abstract. The data on pH changes and corresponding equilibrium shifts of the carbonate system of process and return waters of the circulating cooling system (RCS) of the Rivne NPP during water treatment were analysed. In the additional cooling water previously clarified by liming, there is no dissolved carbon dioxide and no residual free alkalinity. The effects that occur during heating, cooling, and aeration in the RCS cause a shift in the equilibrium of the carbonate cooling water system with a decrease or increase in the content of carbon dioxide, bicarbonate, and carbonate ions, and pH level. The influence of the shift of the carbonate system and the changes in pH level during the discharge of return water from the Rivne NPP into a natural water body (Styr River) was analysed.

1. Introduction

The water is an essential component for the operation of nuclear power plants (NPPs), as it is needed for cooling in the processes of the steam-water cycle [1]. However, wastewater discharges into natural reservoirs can lead to changes in the chemical equilibrium of their components, which is a potential technogenic hazard and requires constant monitoring in the operation of nuclear power plants [2, 3]. Carbon dioxide, bicarbonate and carbonate ions are important parameters for monitoring the water-chemical regime of the NPP cooling system.

These are the main components of the carbonate buffer system of natural waters providing the ability to neutralize acids and determine the alkalinity of water. That is why, in water treatment technologies of the circulating cooling system (RCS) of nuclear power plants, the components of the carbonate system shall meet a number of environmental standards [2], which is also essential in a view of the sustainable development of the entire energy sector [4].

1.1. Literature review

We know that in natural waters, the ratio of carbon dioxide, bicarbonate, and carbonate ions is a forming factor in the pH level of the aquatic environment. Each of the components of the carbonate system of water exists in a certain pH range. If any of these forms is in a given amount, this determines a certain pH value of water, which in turn determines the presence of co-existing forms of carbonates. Dissolved carbon dioxide interacts with water and forms bicarbonate and carbonate ions, and an increase in the water pH level, as an important component of the carbonate equilibrium, leads to a shift in the carbonate equilibrium towards the formation of calcium carbonate [5–7]. When studying river carbonate systems, it was found that in waters with higher alkalinity, atmospheric equilibrium occurs more slowly, since part of the carbon dioxide entering the river stream passes into bicarbonate ions [8]. The result of this direct buffering is a constant preservation of pH, alkalinity index, and an increase in dissolved inorganic carbon index. In addition, the components of the carbonate water system are influenced by the hydrobiological processes. In particular, during the active vegetation season of the planktonic organisms, due to the consumption of carbon dioxide during the aquatic plants' photosynthesis, the carbon dioxide is assimilated with the formation of bicarbonate ions, which is manifested in the increase in water pH levels [9].

In the technological cycles of water cooling systems, the pH value of the water is also influenced by such factors as water temperature, water movement speed, time spent in the system, the intensity of aeration and evaporation of water, as well as the addition of chemical reagents and metallurgy of the system components [10, 11].

For example, in a model study of carbon dioxide release and changes in the carbonate system when heated without aeration, with the formation of calcium carbonate scale, the conditions of multi-stage RCS evaporation were reproduced. It was found that when evaporating without aeration, the pH shifts to higher values and significantly affects the concentration of bicarbonate and carbonate ions in cooling water [12]. The effect of concentration of soluble salts and precipitation of calcium carbonate in return waters was also observed when the cooling water was repeatedly heated in the turbine condenser, which indicated a shift in the equilibrium of the RCS carbonate system [13]. It is also proved that the other chemical components present in industrial cooling systems, after discharges into natural water bodies, make the chemical composition of surface waters more complex and can change their pH value [14]. An important element of safety is scientific studies and engineering achievements aimed at improving design solutions and increasing the reliability of NPP systems and components. The essential service RCS NPP whose reliability, safety, performance of functions and efficiency are influenced by the established water chemistry [15].

1.2. Relevance and goals of research

It is obvious that when operating cooling systems of nuclear power plants, in each specific case it is important to monitor the water-chemical regime of both the RCS itself and the natural water bodies to which their discharge waters fall. This will improve the understanding of the conditions to protect the natural surface waters, and therefore contribute to the environmental safety of the operation of nuclear power plants.

That is why the goal of our research was to analyze the formation of the carbonate system of the Rivne NPP and its influence on changes in the pH levels of the surface waters of the Styr River in order to optimize the use of chemical reagents in water treatment technology minimizing the ecological impact of discharged water on surface waters and improving the effectiveness of the water and chemical regime RCS.

2. Object and methods of research

The carbonate system of process and return water of the Rivne NPP was the object of this study. Water treatment of RCS cooling water is carried out by liming with bicarbonate regime dosage, followed by stabilization treatment with sulphuric acid. The water balance of the RCS of the Rivne NPP is given in (figure 1). Note that in accordance with the national standards of Ukraine requirements regarding the composition and properties of drinking water objects usage,

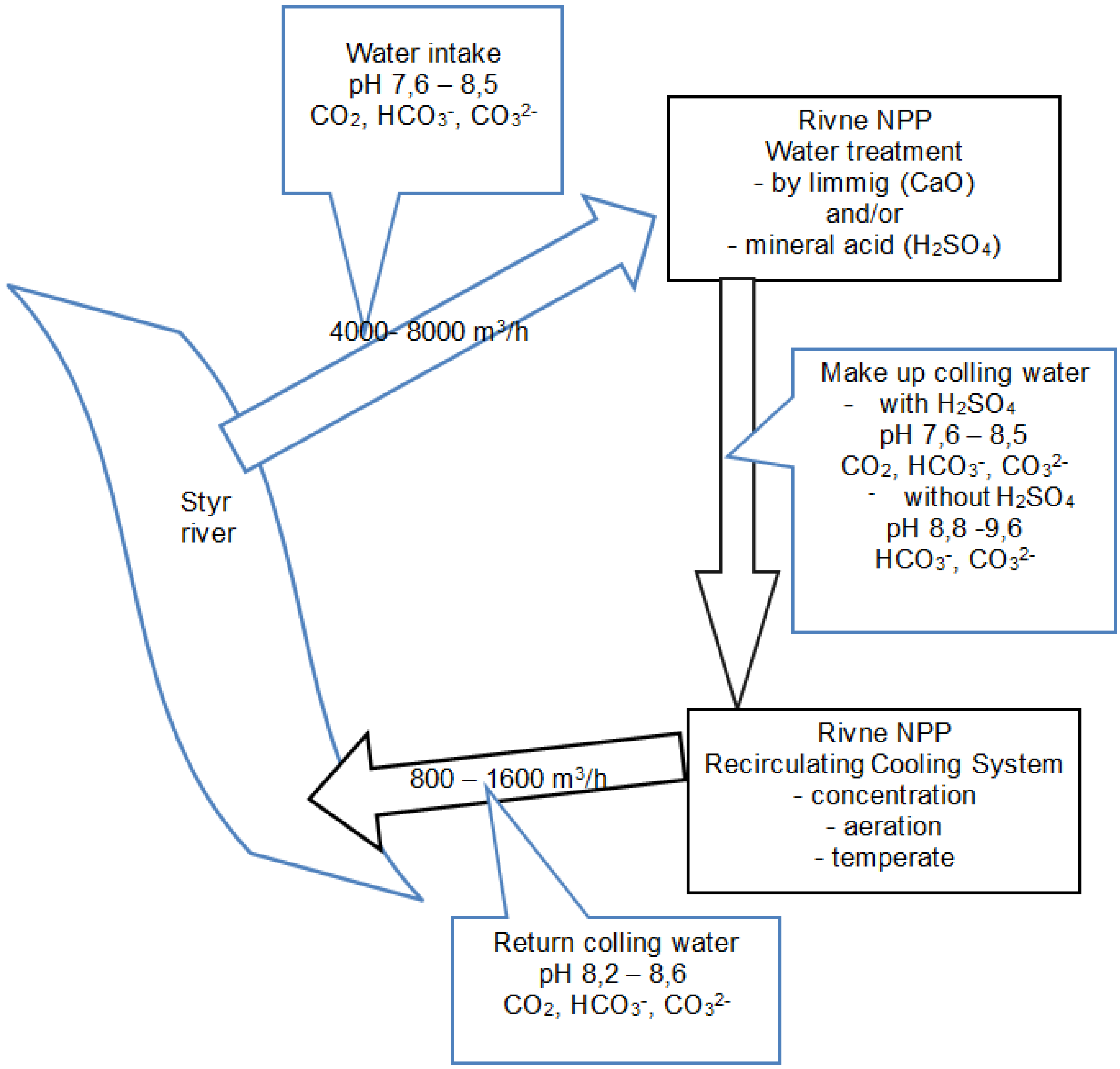

Figure 1. Cooling water balance of the Rivne NPP RCS.

the water of recreation areas reservoirs, as well as the water of fisheries reservoirs should not exceed the values of 6.5-8.5 for pH levels.

The pH was measured with the “I-160” ionometer according to the standard method [16]. The analysis of the chemical control data of RCS was carried out in accordance with the reports on the assessment of the impact of non-radiation factors of the Rivne NPP [17].

3. Results

The dynamics of changes in the pH levels of technological waters of the Rivne NPP and the water of the Styr River are shown in the table 1 and at figure 2, figure 3, respectively. The data shown in the table indicate that the pH level of Styr River meets the requirements of national standards of Ukraine and this is determined by the content of bicarbonate ions.

During water treatment by liming, the pH level increases to 9.4-9.8 units, there is a shift in the carbonate equilibrium with the formation of carbonate ions and precipitation of calcium

Table 1. Descriptive statistics of the results distribution of average annual pH measurements in the process water of the Rivne NPP and the water of the Styr River during water treatment with constant and factorial dose H_2SO_4.

Year	Statistical parameters	pH			
		Styr River, before water intake	Make up cooling water	Return cooling water	Styr River, after water discharge
		During water treatment with constant dose H_2SO_4			
2012	M ± SE	8.34 ± 0.13	7.49 ± 0,06	8.55 ± 0.11	8.40 ± 0.15
	Min–Max	8.13–8.55	7.42–7.60	8.35–8.67	8.17–8.67
	CV	1.55	0.86	1.29	1.83
2013	M ± SE	8.40 ± 0.14	7.50 ± 0,08	8.60 ± 0.10	8.36 ± 0.15
	Min–Max	7.95–8.44	7.33–7.65	8.45–8.78	8.11–8.61
	CV	1.71	1.10	1.11	1.84
2014	M ± SE	8.44 ± 0,17	7.49 ± 0.06	8,63 ± 0,10	8.27 ± 0.18
	Min–Max	8.11–8.65	7,44–7.61	8.45–8.81	8.05–8.42
	CV	2.01	0.77	1.14	2.10
2015	M ± SE	8.27 ± 0.20	7.46 ± 0.03	8.71 ± 0.12	8.31 ± 0.13
	Min–Max	8.05–8.42	7.45–7.51	8.48–8.81	8.08–8.51
	CV	1.52	0.37	1.44	1.56
2016	M ± SE	8,17 ± 0.19	7.50 ± 0,07	8,64 ± 0.10	8,19 ± 0.19
	Min–Max	7.85–8.42	7.44–7.65	8.45–8.88	7.90–8.19
	CV	2.34	0.90	1.19	2.23
		During water treatment with factorial dose H_2SO_4			
2017	M ± SE	8.17 ± 0.23	9.11 ± 0.82	8.44 ± 0.19	8.22 ± 0.22
	Min–Max	7.56–8.43	7.60–9.80	8.15–8.74	7.71–8.49
	CV	2.83	9.00	2.29	2.63
2018	M ± SE	8.13 ± 0.25	9.20 ± 0.60	8.45 ± 0.13	8.24 ± 0.20
	Min–Max	7.82–8.42	7.65–9.80	8.30–8.65	7.95–8.56
	CV	3.05	6.57	1.58	2.48
2019	M ± SE	8.23 ± 0.205	8.80 ± 0.71	8.58 ± 0.24	8.30 ± 0.20
	Min–Max	7.92–8.60	7.61–9.45	8.23–8.81	8.07–8.66
	CV	2.49	5.86	2.80	2.41
2020	M ± SE	8.25 ± 0.21	9.08 ± 0.53	8.62 ± 0.12	8.31 ± 0.17
	Min–Max	7.88–8.50	8.35–9.81	8.38–8.77	8.08–8.52
	CV	2.56	5.86	1.45	2.01
2021	M ± SE	8.16 ± 0.265	9.21 ± 0.52	8.56 ± 0.13	8.21 ± 0.21
	Min–Max	7.65–8.56	8.05–9.80	8.30–8.73	7.85–8.53
	CV	3.25	5.68	1.56	2.62

Note: M is the arithmetic mean pH value; SE is the standard error; Min–Max are minimum and maximum pH values; CV is the coefficient of variation for pH values.

carbonate, the overall hardness is significantly reduced compared to incoming water, and the free alkalinity is formed. During stabilization treatment with sulphuric acid, the alkalinity is neutralized to form bicarbonates. The need for stabilization treatment with sulphuric acid is determined by the quality indicators of RCS cooling water.

Within the work of Rivne NPP RCS, during the period of our research, there were periods of recharge with additional water, neutralized or not neutralized with the sulphuric acid. When feeding with water neutralized with sulphuric acid, an increase in pH level was observed in the RCS cooling water, and the non-neutralized one has a decrease in pH level, which in both cases is due to the accumulation of bicarbonate ions (figure 2, figure 3). Regardless of the method of stabilization treatment, the stabilization of the pH values of RCS cooling water is observed in the range of 8.3-8.7. In all cases, the variation coefficients of the pH change ranges were less than 10%, which indicates their low variability and, consequently, relative constancy of the values.

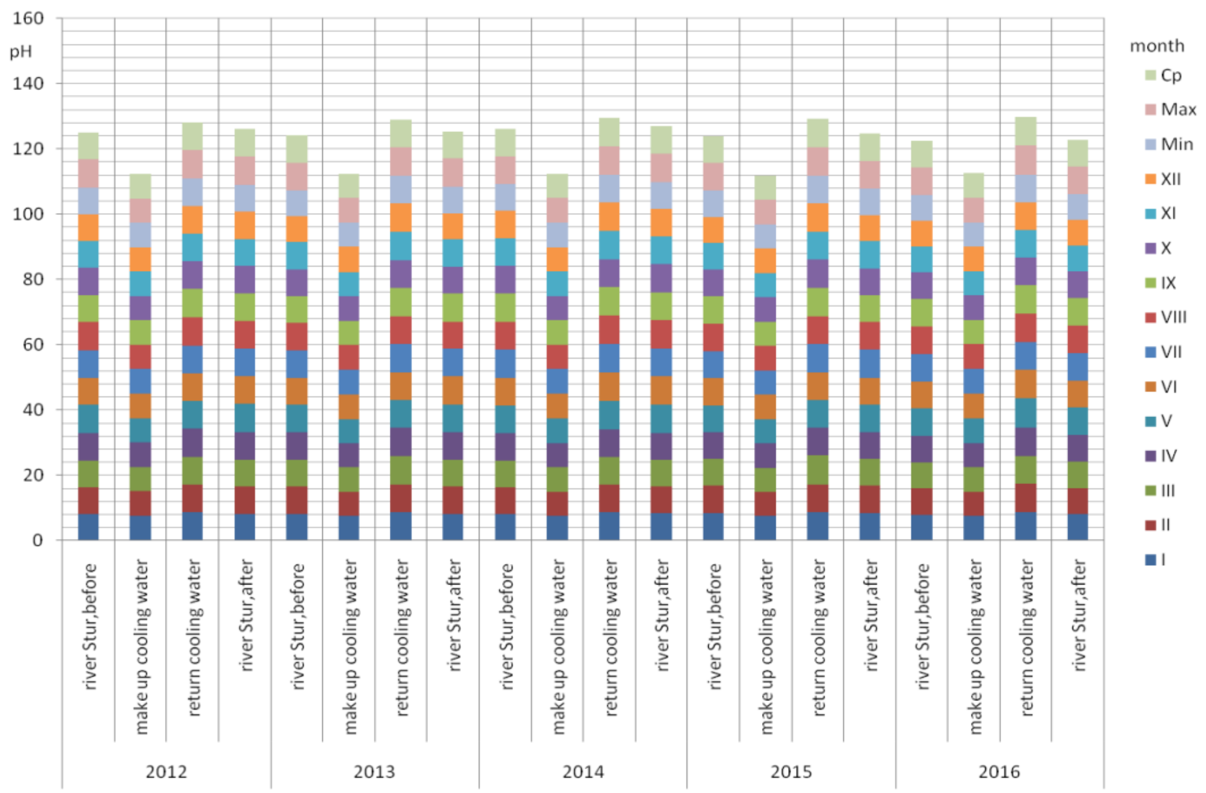

Figure 2. Change of pH in the process water of the Rivne NPP and the water of the Styr River for 2012 – 2016 (diagram with accumulation).

The discharge of return water with a pH level of 8.3-8.7 of the Rivne NPP does not affect the pH values of water in Styr River and compliance with the requirements of national standards of Ukraine (figure 2, figure 3). The data of pH control of the Styr River given in the figure show that the indicator is subject to seasonal fluctuations throughout the year. Thus, in winter, the pH level decreases to 7.5-8.0 units, and in summer it increases up to 7.8-8.5 units.

4. Discussion

When operating RCS, it is important to ensure the water-chemical regime (WCR), in order to prevent the formation of scale, corrosion, and biological interference [2]. According to the results

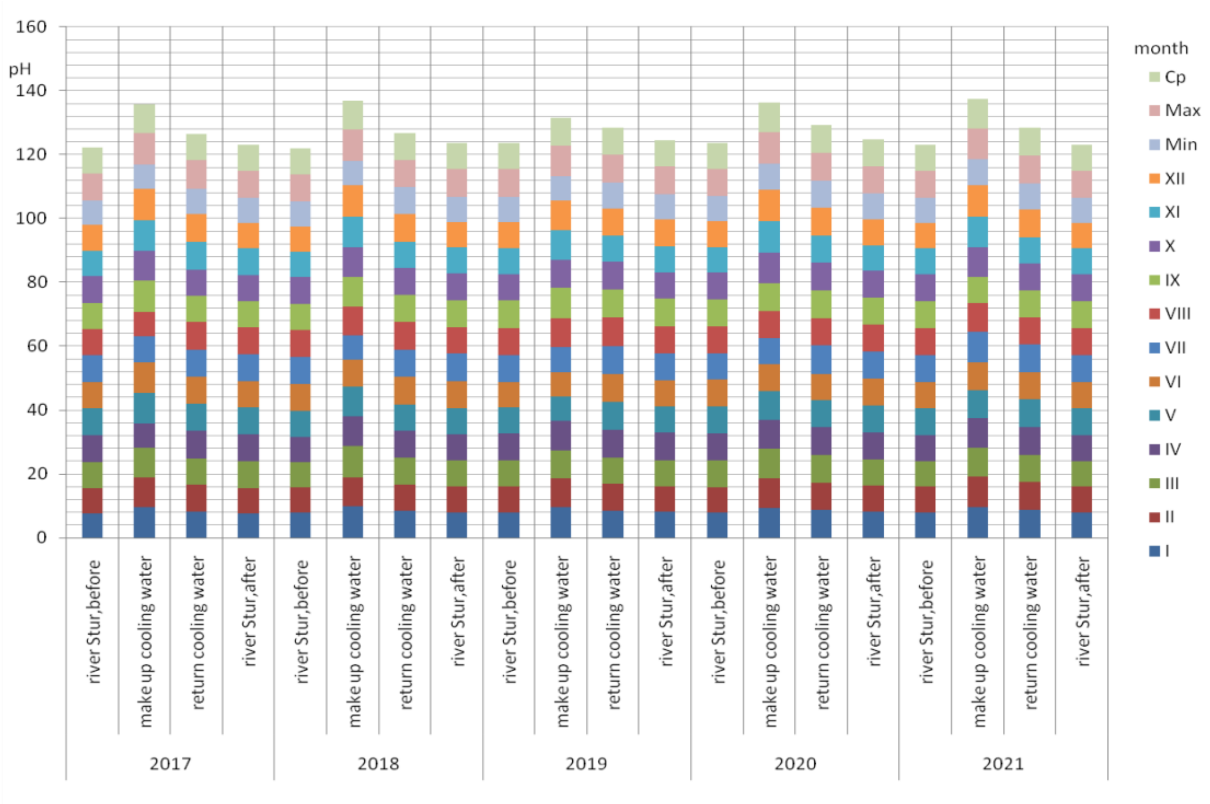

Figure 3. Change of pH in the process water of the Rivne NPP and the water of the Styr River for 2017 – 2021 (diagram with accumulation).

of our research, it was found out that in the technological cycle of the RCS of the Rivne NPP, additional cooling water is completely devoid of carbon dioxide during the pre-liming, and the formation of carbon dioxide occurs when neutralized with sulphuric acid and when heated in heat exchangers by consumers with the release of calcium carbonate sediment. In the cooling tower, when cooling and aeration of cooling water with pH level 9.6 ± 0.2, without pre-stabilization treatment with sulphuric acid, occurs carbon dioxide absorption from the air can be observed to establish the equilibrium of the carbonate system by neutralizing the residual free alkalinity of the pre-limed water, which confirms the control data of cooling and additional water figure 3.

When using untreated inlet water to feed RCS, the scale formation calcium carbonate cannot be prevented even at low levels degree of evaporation for cooling water [13]. Therefore, pre-treatment methods are used, which may include physical, physico-chemical and chemical methods of water treatment. Liming is one of the most common technological solutions for water treatment [10]. The dose of lime used for water treatment determines the value of the pH values of the additional cooling water.

According to the results of our research, during the stabilization treatment with constant sulphuric acid (table 1, figure 2), the free alkalinity of pre-limed cooling water with pH 7.5-7.8 values is already neutralized, the absorption of carbon dioxide from the air with neutralization of the residual free alkalinity in the cooling tower does not occur, when cooling in the cooling tower, it is possible to release carbon dioxide formed during the deposition of calcium carbonate by reaction with an increase in the hydrogen pH index, which is due to the concentration of the sample during evaporation and accumulation of bicarbonate ions for cooling water that has been limed and treated with sulphuric acid and does not contain free alkalinity.

The properties of the carbonate system of water during the stabilization treatment with factorial dosage sulphuric acid (table 1, figure 3) depend on the course of two competing reactions that cause the dissolution of carbon dioxide during aeration with the formation of bicarbonate ions, with a decrease in pH level, and, when evaporation in RCS by the decomposition of bicarbonate ions and the formation of carbonate ions, which increases pH level [12]. That is, the initial distribution state of the carbonate system components determined by the initial pH level is the determining factor for shifting the equilibrium of reactions.

We have noticed seasonal fluctuations in the pH value in Styr River. In particular, a decrease in its values in winter and an increase in summer can be explained by seasonal features of the phytoplankton groups development and an increased manifestation of their photosynthetic activity during the warm period [9]. That is, the change in the pH balance of the surface waters of the Styr River during the year is primarily related to the natural factors.

5. Conclusions

In the study of the equilibrium of the carbonate system in the process waters of the RCS of the Rivne NPP and the natural waters of the Styr river, it was found out that the use of stabilization treatment with sulphuric acid in water treatment (solely to ensure environmental standards for the pH value) is impractical.

Results of factorial and constant sulphuric acid dosing have comparable pH values of the cooling water, therefore accumulation of bicarbonate ions and neutralization of carbonate ions from an ecological point of view does not compensate for the artificial introduction of sulphate ions into natural objects for the use of sulphuric acid only to reduce the pH level of water in order to ensure environmental standards. It is advisable to use sulphuric acid only to normalize the water-chemical regime. Taking this fact into account will optimize the RCS water treatment technology of the Rivne NPP with a guarantee of compliance with the environmentally safe water-chemical regime of the discharge water on the Styr river. RCS are widespread project decision for cooling components and systems of power plants, these results of the study can be also applied to any power plant with RCS, where the pre-treatment of cooling water by liming and stabilization treatment with mineral acid is implemented.

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References

[1] Macknick J, Newmark R, Heath G and Hallett K C 2012 *Environmental Research Letters* **7**(4) 045802 URL `https://doi.org/10.1088/1748-9326/7/4/045802`
[2] Lim-Wavde K, Zhai H, Kauffman R J and Rubin E S 2018 *Energy Policy* **120** 714–733 URL `https://doi.org/10.1016/j.enpol.2018.05.067`
[3] Argüelles R, Toledo M and Martín M 2021 *Chemosphere* **279** 130532 URL `https://doi.org/10.1016/j.chemosphere.2021.130532`
[4] Cole J J and Prairie Y T 2014 Dissolved co2 in freshwater systems *Reference Module in Earth Systems and Environmental Sciences* (Elsevier) URL `https://doi.org/10.1016/b978-0-12-409548-9.09399-4`
[5] 2017 FACT SHEET: Clean Energy Incentive Program URL `https://archive.epa.gov/epa/cleanpowerplan/fact-sheet-clean-energy-incentive-program.html`
[6] Osadchaya N N and Osadchiy V I 2002 *Issues of Chemistry and Chemical Technology* (5) 250–254 ISSN 0321-4095
[7] Mitchell M J, Jensen O E, Cliffe K A and Maroto-Valer M M 2009 *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences* **466** 1265–1290 URL `https://doi.org/10.1098/rspa.2009.0349`
[8] Stets E G, Butman D, McDonald C P, Stackpoole S M, DeGrandpre M D and Striegl R G 2017 *Global Biogeochemical Cycles* **31**(4) 663–677 URL `https://doi.org/10.1002/2016gb005578`

[9] Ramos e Silva C A, Monteiro N S C, Cavalcante L M, Junior W T, Rocha Carneiro M E, Soares de Souza F E, Borges Garcia C A, Damasceno R N and de Araújo Rocha A 2022 *PLOS ONE* **17**(7) URL https://doi.org/10.1371/journal.pone.0271875
[10] Khoruzhyi P D, Khomutetska T P and Khoruzhyi V P 2008 *Resource-saving water supply technologies* (Kyiv: Agrarian Science)
[11] Meier D A, Chen B and Myers C 2022 Cooling water systems: An overview *Water-Formed Deposits* (Elsevier) pp 239–267 URL https://doi.org/10.1016/b978-0-12-822896-8.00020-0
[12] Al-Rawajfeh A E, Glade H and Ulrich J 2005 *Desalination* **182**(1-3) 209–219 URL https://doi.org/10.1016/j.desal.2005.04.013
[13] Si Z, Xiang J and Han D 2022 *Chemical Engineering and Processing - Process Intensification* **171** 108734 URL https://doi.org/10.1016/j.cep.2021.108734
[14] Sharma S and Bhattacharya A 2016 *Applied Water Science* **7**(3) 1043–1067 URL https://doi.org/10.1007/s13201-016-0455-7
[15] Kuznietsov P and Biedunkova O 2023 *Nuclear and Radiation Safety* **1**(97) 30–40
[16] 2007 MVI No. 081/12-0317-06 Surface, underground, return water. The method of measuring the pH indicator (pH) by the electrometric method URL http://online.budstandart.com/ua/catalog/doc-page?id_doc=76469
[17] Reports on the assessment of the impact of non-radiation factors of SS "Rivne NPP" SE "Energoatom" on the environment for 2013-2021

Neural network model of investment process of biogas production

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Neural network model of investment process of biogas production

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Abstract. The paper forms a neural network model of the investment process of biogas production, which allows increasing the efficiency of the management decision-making process on the feasibility of investing in biogas plants. Biogas plants are becoming widespread in the world, although natural climatic conditions are not favorable for biogas production. But modern technological solutions for insulation of bioreactors, their automation and thermal stabilization, allow obtaining biogas in different latitudes. The construction of biogas plants requires significant capital investment. Therefore, these investments require a detailed feasibility study, including consideration of both technical and economic aspects of biogas production. The authors propose to use the mathematical apparatus of shallow neural networks and create a ten-neuron shallow neural mathematical model with the MATLAB mathematical package, which can serve as a tool to support investment decisions in the implementation of the biogas plant project. The proposed model, in contrast to existing approaches, allows us to take into account both quantitative and qualitative factors, which are obtained analytically, expertly and experimentally. In addition, the proposed model allows combining both economic and technical criteria that affect the decision-making process for investing in the process of biogas production. The calculation of investment attractiveness of introduction of biogas utilization unit for the researched enterprise is given. According to the simulation results, it is determined that the investment attractiveness of the introduction of a biogas plant for the given set of input factors indicates the feasibility of implementing a biogas plant.

1. Introduction

In today's world of economics, humanity faces several important issues related to sustainable development, among which the important goals are to increase the production of energy from renewable sources around the world and ecological production. Permanent increase in energy prices causes a constant increase in production costs and reduces profits. One of the ways to ensure energy saving measures is to use biogas as an alternative energy source. This issue is especially relevant for agricultural producers and the food industry, as they regularly receive a significant amount of organic waste, which should be transformed into biogas. The use of biogas as a way to overcome the energy crisis in developing countries is considered [1]. Yu et al [2] analyzed the complex productivity of single-phase and two-phase anaerobic digestion using a hybrid method and determined that the decisive factors are the yield of biogas, electricity consumption and biofertilizers.

The results of research by Nwokolo et al [3] allow us to conclude that the use of biogas plants provides benefits such as reducing greenhouse gas emissions into the environment and improving energy security. In addition, the use of produced biogas leads to a reduction in purchased energy and waste disposal in the biogas plant based on the system of sewage sludge treatment at treatment plants.

In Europe, biogas is produced in a large number of countries, including Poland [4], Finland [5], Germany [6], Hungary [7]. In particular, more than 1,000 biogas plants were built in Germany from 2000 to 2014 [8]. Some questions connected with the state of biofuel in Ukraine are considered by Stanytsina et al [9], Bogoslavska et al [10].

The construction of biogas plants requires significant capital investment. Therefore, these investments require a detailed feasibility study, including consideration of both technical and economic aspects of biogas production. Nurgaliev et al [11] proposed to assess the efficiency of investing in biogas plants by calculating the classic performance indicators of investment projects with and without discounting, given the rapid change in variables.

Taking into account quantitative and qualitative factors, which are obtained analytically, expertly and experimentally, requires a specialized mathematical apparatus. The best mathematical apparatus, in our opinion, is either the theory of fuzzy logic and linguistic variables or the theory of neural networks.

The aim of the work is to form a neural network model of the investment process of biogas production, which allows us to increase the efficiency of the management decision-making process on the feasibility of investing in biogas plants.

Fuzzy logic theory uses a limited information base, within which fuzzy logical equations are formed and the result is calculated [12–15]. Fuzzy logic theory works in a closed information environment, which is limited by knowledge bases. Neural networks are used for processing large data sets, universal approximation and further training of mathematical models. The neural network is a universal approximator, which is an example of artificial intelligence and allows you to support decision-making based on the results of processing large arrays of quantitative and qualitative information. It is proposed to use the mathematical apparatus of shallow neural networks and create a ten-neural shallow neural mathematical model with the MATLAB mathematical package, which can serve as a tool to support investment decisions in the implementation of the biogas plant project.

2. Results and discussion

The production of agricultural products is accompanied by the constant accumulation of organic waste from animal life, crop products, wood processing, etc. Ukraine produces more than 57,000 tons of organic waste annually [16], the vast majority of which simply pollutes the environment. All these wastes require proper and safe disposal, preferably with the simultaneous production of products necessary for agriculture. One of such directions of ecologically safe utilization of organic waste is biogas production. The process of anaerobic fermentation in bioreactors allows you not only to dispose of environmentally hazardous waste, but also to process it into biogas and valuable organic fertilizer.

Biogas plants are becoming widespread in the world, although natural climatic conditions are not favorable for biogas production. But modern technological solutions for insulation of bioreactors, their automation and thermal stabilization, allow us to obtain biogas in different latitudes. A biogas plant is a complex set of interconnected technological elements of the process of utilization of organic waste with their processing into biogas and biofertilizers. The central element of the biogas plant is a bioreactor, that is an insulated tank with a heating element, stirrer, devices for loading the substrate and removing it, gasholder, process control devices. The process of anaerobic fermentation takes place in a bioreactor, but before the raw material enters the reactor, it must go a long way of collection and preparation. First of all, organic waste must be delivered to the site, then crushed and mixed with water, fed at a certain temperature to the reactor. The output of biogas from different types of organic waste is also different (table 1).

The process of anaerobic fermentation is also significantly influenced by the temperature of

Table 1. Biogas yield and methane content when using different types of waste [3].

Output raw materials	Biogas yield per 1 kg of dry matter	Methane content,%
Waste from cattle	200–300	50
Waste from pigs	340–480	60...75
Horse waste with straw	250	56...60
Potato tops	420	60
Maize stalks	420	53
Wheat straw	342	58
Sunflower husk	300	60
Silage	250	84
Fresh grass	360	52
Beet	430	84
Carrot waste	250	60
Wood sawdust	220	51
Solid sewage sludge	570	70
Fecal sediment	250 – 310	60
Household waste and rubbish	600	50

the fermentation regime, thermal stabilization in the volume of the bioreactor, the fineness of raw materials, etc. In addition to complex technical requirements for the implementation of the waste processing process, the investment process of such a decision is subject to significant restrictions on financial, economic and operational requirements.

Biogas can be burned directly, but taking into account the large number of impurities (about 40% CO_2 + other gases 1..3%), it is better to clean it first. From 1 m^3 of biogas with a methane content of 60%, you can get about 2.5 kWh of electricity, or 2.6 kWh of heat.

The process of implementation of the investment decision on the implementation of the disposal plant requires the assessment of many factors of influence, which have both quantitative and qualitative characteristics. Biogas plants require significant capital investment, stable supply of the reactor with heat and electricity, continuous supply of raw materials, maintenance of temperature in the fermentation environment, etc. The decision to implement a biogas plant at the enterprise must be made comprehensively using modern advances in science and technology. In our opinion, in this case, the optimal method of intellectual decision support is the theory of neural networks [17, 18]. This theory allows us to combine into a single mathematical model quantitative and qualitative factors of the technological process of fermentation, as well as financial, economic and operational components of the process of disposal of organic waste as an investment object. The decision to implement a biogas plant must be made taking into account a large number of influencing factors. Significant cost of installations requires careful analysis of all risks and features of the technological process. In addition to the complex technological requirements for the process of anaerobic fermentation related to the quality of raw materials, temperature and humidity of the substrate, there are a number of human factors related to qualifications, motivation and other factors. In general, we propose to determine the degree of feasibility of implementing a biogas plant by the values of investment attractiveness. For this indicator D, we have proposed ranges of values of factors in which it acquires a certain content saturation. If D belongs to the range of values [0...2], then the implementation of the project for the construction of a biogas plant is impractical. In the range [2...4] the investment attractiveness of the construction process biogas plant is below average, in the range (4...6) it is average, in the range (6...8) it is above average; in the range [8...10] it is the maximum investment attractiveness of the process of implementing biogas plant.

The investment attractiveness of the introduction of biogas disposal plant can be considered in the form of the ratio:

$$\mathrm{D} = f(\mathrm{X}, \mathrm{Y}, \mathrm{Z}), \tag{1}$$

where X is a set of financial and economic factors; Y is a set of technical factors; Z is a set of operational factors.

In turn, the above sets of factors can be deployed in the following dependences:

$$\mathrm{X} = f(\mathrm{x}_1, \mathrm{x}_2, \mathrm{x}_3, \mathrm{x}_4, \mathrm{x}_5), \tag{2}$$

$$\mathrm{Y} = f(\mathrm{y}_1, \mathrm{y}_2, \mathrm{y}_3, \mathrm{y}_4), \tag{3}$$

$$\mathrm{Z} = f(\mathrm{z}_1, \mathrm{z}_2, \mathrm{z}_3, \mathrm{z}_4). \tag{4}$$

Detailed characteristics of factors influencing the investment process, their universal set of variations and linguistic terms for evaluation are given in table 2.

Group of financial and economic factors:

- Factor x_1 – linguistic variable (LV) "Qualification level of personnel" characterizes the level of qualification of personnel that will service the biogas plant. Linguistically, we decided to evaluate this factor in terms of "insignificant, medium, high". It is clear that the higher the qualification level of staff is, the more attractive the process of implementing this decision is.
- Factor x_2 – LV "Dependence on external financing entities" characterizes the degree of borrowed capital in total investment capital and the cost of borrowed capital. The higher the share of borrowing is and the higher the cost of such capital is, the less attractive the investment is.
- Factor x_3 – LV "Level of raw material costs" characterizes the level of raw material costs for a biogas plant. Raw materials can be provided free of charge; raw materials utilization can be paid for or they have to be bought. Purchasing raw materials for biogas production is the least advantageous option when considering alternatives.
- Factor x_4 – LV "Level of capital costs" characterizes the amount of capital investment for the construction of a biogas plant in terms of 1 kWh of electricity produced from biogas. According to research results, depending on the type of raw material and temperature regime, this factor may be in the range of 2...10 thousand euros/kWh. It is clear that the higher the level of capital expenditures is, the riskier the investment is.
- The last factor from the financial and economic block is x_5 – LV "Complexity of logistics" characterizes the complexity of delivery of raw materials for the operation of biogas plants and transportation and storage of fermentation products – biogas and biofertilizers to consumers. The volume of processed biomass is slightly different from the input volume of raw materials, and it can be applied to the fields only in spring or autumn. Therefore, the rest of the time the processed biomass must be stored somewhere. Most of the above factors are estimated in conditional points expertly as it is almost impossible to quantify them.

Group of technical factors:

- Factor y_1 – "Type of raw material". Raw materials play an important role in the process of biogas production. The best raw material is sugar pulp or waste, which contains a large proportion of fat. Potato tops, corn stalks, cattle and pig waste are more difficult to decompose in the bioreactor. The "worst" ones are silage and sawdust.

Table 2. Influencing factors as linguistic variables.

Designation and name of the variable	Universal set	Linguistic terms for evaluation
	Financial and economic factors (X)	
x_1 – LV – "Qualification level of personnel"	$U(x_1) = \{1...10\}$ (points)	insignificant, medium, high
x_2 – LV "Dependence on external financing entities"	$U(x_2) = \{0...10\}$ (points)	insignificant, medium, high
x_3 – LV "Level of raw material costs"	$U(x_1) = \{1...10\}$ (points)	low, medium,high
x_4 – LV "Level of capital costs per 1 kWh of electrical energy"	$U(x_4) = \{2...10\}$ (thousand euros)	small, medium, high
x_5 – LV "Complexity of logistics"	$U(x_5) = 1 ... 10$ (points)	low, medium, high
	Technical factors (Y)	
y_1 – LV "Type of raw material"	$U(y_1) = 1...10$ (points)	acceptable, satisfactory, optimal
Y_2 – LV "Crushing of raw materials"	$U(_y2) = 1...10$ (points)	insignificant, medium, high
y_3 – LV "Temperature mode"	$U(y_3) = 20...55$ (degrees, °C)	cryophilic, mesophilic, thermophilic
Y_4 – LV "Thermal stabilization of the fermentation process"	$U(y_4) = 20...3$ (degrees °C)	insufficient, medium, high
	Operational factors (Z)	
Z_1 – LV "Technical complexity of the operational process"	$U(z_1) = 10\ 90$ (percent)	insignificant, medium, high
Z_2 – LV "Level of purification of biogas from impurities"	$U(z_2) = 0\ 99$ (points)	low, medium, high
Z_3 – LV "Level of automation of the production process"	$U(z_3) = 10\ 90$ (percent)	low, medium, high
Z_4 – LV "Degree of reduction of harmful emissions into the environment"	$U(z_4) = 10\ 90$ (percent)	low, medium, high

- Equally important is the crushing of raw materials, which is described visually by experts in the range of {1...10} points – factor y_2. The intensity of the anaerobic fermentation process is directly dependent on the ambient temperature.
- There are three main temperature regimes: "cryophilic" ($T_{opt} = 20°C$); "mesophilic" ($T_{opt} = 3242°C$); "thermophilic" ($T_{opt} = 4851°C$). Factor y_3 – LV "Temperature mode" characterizes the temperature regime in the reactor in the range 20...55°C. The temperature in the environment should be uniform. This is quite difficult to achieve, given the large volumes of the reactor, the presence of stagnant zones under the heating elements, the technological limitations of the mixing speed of the substrate. Thermal stabilization of the fermentation process is estimated by the value of the temperature difference between the hottest and the coldest zone of the reactor volume. It is generally accepted that the temperature difference in the reactor zone should not exceed 3 °C.

Main *operational factors*:

- The technical complexity of the operational process is assessed by experts and is in the range from [10...90]%.
- The level of purification of biogas from impurities is estimated in the range [0... 99]% and is determined by technological calculations.
- The level of automation of the production process and the degree of reduction of harmful emissions into the environment are estimated in the same range.

To develop a mathematical model of intellectual support of decision-making to assess the investment attractiveness of a biogas plant project, there is a need to form a knowledge matrix – concentrated coded information determined by technological calculations, expert evaluations, analytical calculations. The knowledge matrix is a table where the numerical value shows the results of various types of research. The fragment of the knowledge matrix is given in table 3. The sample size for building the model was more than 200 data rows.

Table 3. The fragment of the knowledge matrix.

x_1	x_2	x_3	x_4	x_5	y_1	y_2	y_3	y_4	z_1	z_2	z_3	z_4	D
10	0	1	2	1	10	10	55	3	10	99	90	90	10
8	2	3	3	2	8	8	55	5	20	85	80	80	9
9	3	2	4	3	7	7	35	7	30	70	70	70	8
.	.	.	.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.	.	.	.
4	7	6	7	7	4	3	35	12	60	30	25	25	4
3	8	7	8	8	3	4	20	15	80	20	20	20	3
2	9	8	9	9	2	3	35	18	70	10	15	15	2
1	10	10	10	10	1	1	20	20	90	0	10	10	1

To build a neural network that would solve the problem with some accuracy, we propose to use a shallow neural network, the block diagram of which is shown in figure 1.

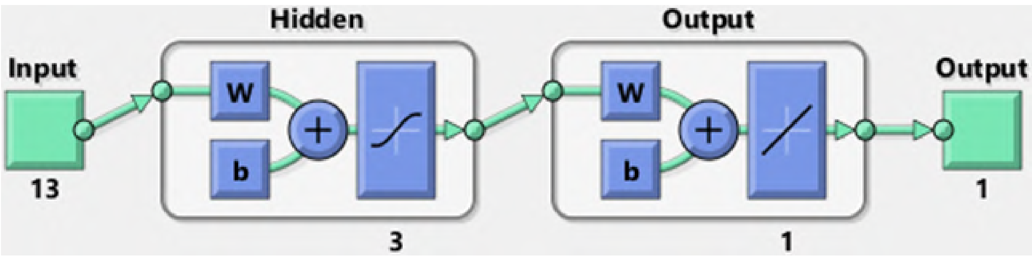

Figure 1. Block diagram of a two-layer neural shallow network.

A two-layer network of direct feed with hidden sigmoid neurons and neurons of linear output can quite successfully solve the problem without excessive accuracy and complexity of calculations (figure 2). This network can also be called a Multilayer Perceptron (MLP) as it is a two-layer neural network with a nonlinear hidden layer that can be used for classification and regression tasks.

The network will be studied according to the Levenberg-Marquardt backpropagation algorithm. The Levenberg-Marquardt algorithm is an optimization method used for adjusting

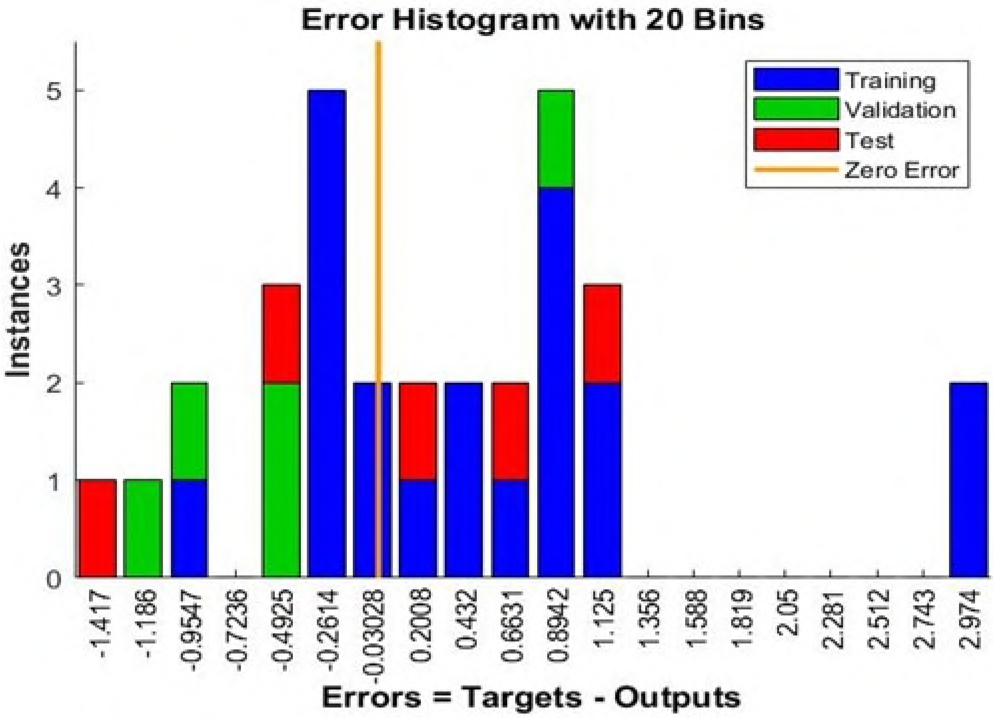

Figure 2. Histogram of errors.

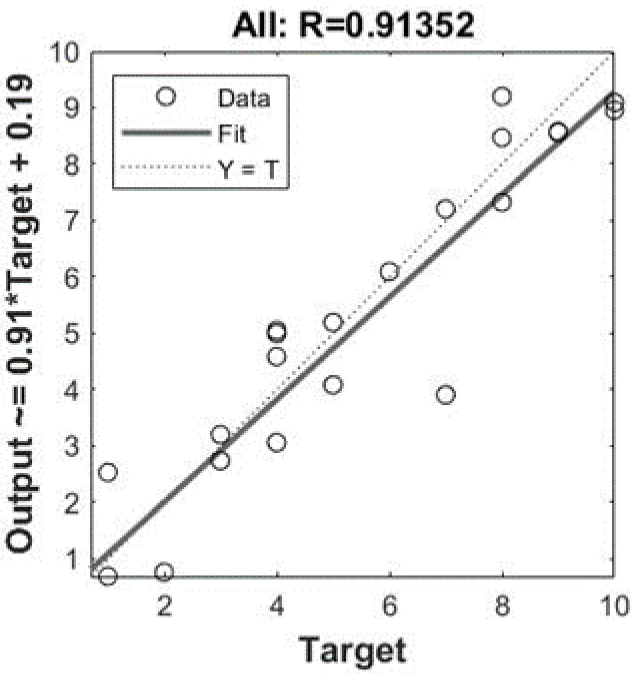

Figure 3. Regression and value of the coefficient of determination.

the weights of a neural network during training. This algorithm is an iterative method based on gradient descent and is designed to solve optimization problems with nonlinear constraints. After loading the data into the MATLAB mathematical package, we performed calculations and determined the calculation errors (figure 3), as well as made a regression graph and determined the coefficient of determination, which in our case was R = 0.91, indicating a high connection density.

For practical use of the proposed model, it is best to create a Simulink model in the MATLAB package. This model has only three blocks: the constant block, where the input values are entered in the form of a vector; the block of the neural network and the visualization block.

In our case – the monitor, where the simulation result is shown as a number (figure 4).

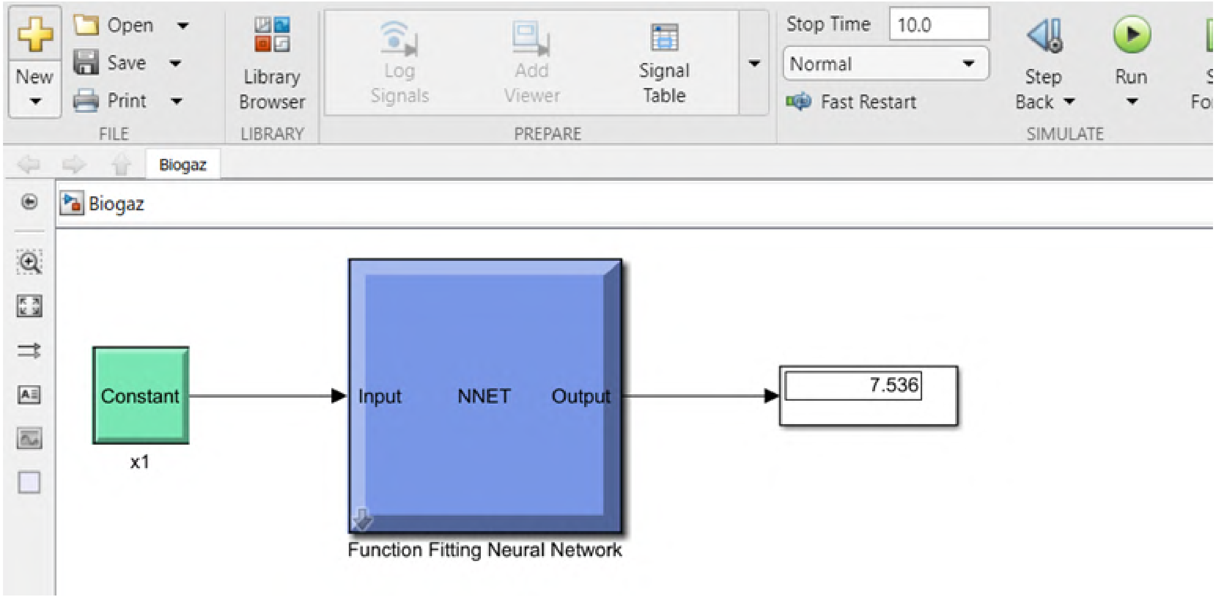

Figure 4. Fragment of the window of the Simulink package of the MATLAB program with the program of neural network modeling.

The decision-making on the feasibility of investing in the construction of a biogas plant is as follows: analytically, expertly or experimentally, the input values are entered into the table. Then their values are loaded into the vector column of the program.

After the calculation, the program displays on the block the value of the investment attractiveness of the introduction of biogas disposal plant (table 4).

According to the simulation results, it is determined that the investment attractiveness of the introduction of a biogas plant with a given set of input factors is D = 7.54, which corresponds to the range "above average", i.e. the plant can be implemented.

3. Conclusions

Thus, the paper proposes a neural network model of the investment process of biogas production.

Taking into account quantitative and qualitative factors, which are obtained analytically, expertly and experimentally, requires a specialized mathematical apparatus. The best mathematical apparatus, in our opinion, is either the theory of fuzzy logic and linguistic variables or the theory of neural networks.

It is proposed to use the mathematical apparatus of shallow neural networks and create a ten-neuron shallow neural mathematical model with the MATLAB mathematical package, which can serve as a tool to support investment decisions in the implementation of the biogas plant project.The proposed model, in contrast to existing approaches, allows us to take into account both quantitative and qualitative factors, which are obtained analytically, expertly and experimentally.

Table 4. Values of input and output variables.

Designation and name of the variable	Universal set	Input values of variables	The value of the output variable D
	Financial and economic factors (X)		
x_1 LV – "Qualification level of personnel"	$U(x_1) = \{1...10\}$ (points)	7	
x_2 – LV "Dependence on external financing entities"	$U(x_2) = \{0...10\}$ (points)	3	
x_3 – LV "Level of raw material costs"	$U(x_1) = \{1...10\}$ (points)	6	
x_4 – LV "Level of capital costs per 1 kWh of electrical energy"	$U(x_4) = \{2...10\}$ (thousand euros)	5	
x_5 – LV "Complexity of logistics"	$U(x_5) = 1 \ldots 10$ (points)	3	
	Technical factors (Y)		
y_1 – LV "Type of raw material"	$U(y_1) = 1...10$ (points)	8	
Y_2 – LV "Crushing of raw materials"	$U(_y2) = 1...10$ (points)	3	D=7.54
y_3 – LV "Temperature mode"	$U(y_3) = 20...55$ (degrees, °C)	50	
Y_4 – LV "Thermal stabilization of the fermentation process"	$U(y_4) = 20...3$ (degrees °C)	8	
	Operational factors (Z)		
Z_1 – LV "Technical complexity of the operational process"	$U(z_1) = 10\ 90$ (percent)	20	
Z_2 – LV "Level of purification of biogas from impurities"	$U(z_2) = 0\ 99$ (points)	60	
Z_3 – LV "Level of automation of the production process"	$U(z_3) = 10\ 90$ (percent)	50	
Z_4 – LV "Degree of reduction of harmful emissions into the environment"	$U(z_4) = 10\ 90$ (percent)	70	

In addition, the proposed model allows us to combine both economic and technical criteria that affect the decision-making process for investing in the process of biogas production. The calculation of investment attractiveness of introduction of biogas utilization unit for the researched enterprise is given.

According to the simulation results, it is determined that the investment attractiveness of the introduction of a biogas plant for the given set of input factors indicates the feasibility of implementing a biogas plant.

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References

[1] Ahmad S, Razzaq S, Rehan M A, Hashmi M A, Ali S, Amjad M S and Mehmood U 2019 *International Journal of Renewable Energy Research* **9**(3) 1537–1547 URL `https://doi.org/10.20508/ijrer.v9i3.9306.g7742`

[2] Yu Q, Li H, Deng Z, Liao X, Liu X and Liu J 2020 *Journal of Cleaner Production* **263** 121625 URL `https://doi.org/10.1016/j.jclepro.2020.121625`

[3] Nwokolo N, Mukumba P, Obileke K and Enebe M 2020 *Processes* **8**(10) 1224 URL `https://doi.org/10.3390/pr8101224`

[4] Klimek K, Kapłan M, Syrotyuk S, Bakach N, Kapustin N, Konieczny R, Dobrzyński J, Borek K, Anders D, Dybek B, Karwacka A and Wałowski G 2021 *Energies* **14**(21) 7375 URL `https://doi.org/10.3390/en14217375`

[5] Ervasti S, Vainio M and Tampio E 2019 *Open Agricultural* **4**(1) 650–660 URL `https://doi.org/10.1515/opag-2019-0065`

[6] Csikos N, Schwanebeck M, Kuhwald M, Szilassi P and Duttmann R 2019 *Sustainability* **11**(9) 2500 URL `https://doi.org/10.3390/su11092500`

[7] Soha T, Papp L, Csontos C and Munkácsy B 2021 *Renewable and Sustainable Energy Reviews* **141** 110822 ISSN 1364-0321 URL `https://doi.org/10.1016/j.rser.2021.110822`

[8] Yang X, Liu Y and Thrän D 2021 *Energy, Sustainability and Society* **11** 6 URL `https://doi.org/10.1186/s13705-021-00282-9`

[9] Stanytsina V, Artemchuk V, Bogoslavska O, Zaporozhets A, Kalinichenko A, Stebila J, Havrysh V and Suszanowicz D 2022 *Energies* **15**(19) 7215 URL `https://doi.org/10.3390/en15197215`

[10] Bogoslavska O Y, Stanytsina V V, Artemchuk V O, Maevsky O V, Garmata O M, Lavrinenko V M and Zinovieva I S 2022 *IOP Conference Series: Earth and Environmental Science* **1049**(1) 012018 URL `https://doi.org/10.1088/1755-1315/1049/1/012018`

[11] Nurgaliev T, Koshelev V and Müller J 2023 *BioEnergy Research* **16**(2) 1084–1098 ISSN 1939-1242 URL `https://doi.org/10.1007/s12155-022-10484-4`

[12] Menind A and Olt J 2009 Biogas plant investment analysis, cost benefit and main factors *Engineering for Rural Development. Jelgava, 28.-29.05.2009* pp 339–343 URL `https://www.researchgate.net/publication/242547266`

[13] Dzhedzhula V, Yepifanova I and Kravchyk Y 2022 Use of the Theory of Fuzzy Sets in Determining the Level of Enterprise Security *2022 12th International Conference on Advanced Computer Information Technologies (ACIT)* pp 311–315 URL `https://doi.org/10.1109/ACIT54803.2022.9913150`

[14] Yepifanova I and Dzhedzhula V 2021 *WSEAS Transactions on Environment and Development* **17** 556–565 URL `https://doi.org/10.37394/232015.2021.17.53`

[15] Chaikovska I I, Hryhoruk P M and Chaikovskyi M Y 2021 Fuzzy model for complex risk assessment of an enterprise investment project *Proceedings of the Selected and Revised Papers of 9th International Conference on Monitoring, Modeling & Management of Emergent Economy (M3E2-MLPEED 2021), Odessa, Ukraine, May 26-28, 2021* (*CEUR Workshop Proceedings* vol 3048) ed Kiv A E, Soloviev V N and Semerikov S O (CEUR-WS.org) pp 163–179 URL `https://ceur-ws.org/Vol-3048/paper09.pdf`

[16] State Statistics Service of Ukraine 2023 Economic statistics / Environment URL `https://www.ukrstat.gov.ua/operativ/menu/menu_u/ns.htm`

[17] Aggarwal C C 2018 *Neural Networks and Deep Learning: A Textbook* (Cham: Springer) URL `https://doi.org/10.1007/978-3-319-94463-0`

[18] Gurney K 1997 *An Introduction to Neural Networks* (London and New York: UCL Press) URL `http://www.macs.hw.ac.uk/~yjc32/project/ref-NN/Gurney_et_al.pdf`

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Assessment of environmental risk of water bodies in the conditions of mineral deposits development

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Assessment of environmental risk of water bodies in the conditions of mineral deposits development

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Abstract. A brief analysis of the mining industry impact on the environment is provided. It is proposed to assess the ecological situation of water bodies on the territory of Iron Ore Dressing Works (GOK) according to the magnitude of ecological risk (e.g. Iron Ore Dressing Works (Northern GOK)). Calculations of ecological risk values based on the content of microcomponents in the water were carried out for man-made (tailings storage) and natural water bodies (the Saksahan river, a pond in the Nedayvoda stream). It was concluded that over time (from 2014 to 2020) the ecological risk of most water bodies is increasing from 0.17 in the Saksahan river to -2.53 in tailings storage. The complex ecological situation on the territory of the Northern GOK proves the need to implement more effective environmental protection measures in order to achieve the criteria of sustainable development.

1. Introduction

The growth of humanity's needs set the global task of providing food with the necessary caloric content and composition, water of an acceptable quantity and quality, territory that provides many aspects of human activity, energy that does not cause global geo-ecological crises, and products of industrial activity that do not lead to an unacceptable level of environmental pollution. These needs are steadily growing, moving the ecosphere from a crisis, but still stable state to an unstable one and with further development of instability – to a global catastrophe.

The mining activity of the regions significantly affects their sustainable development. It can be a source of employment for local residents, a source of state income, an engine of economic growth and development of remote areas. However, significant environmental impacts and inequitable distribution of economic benefits can exacerbate instability and cause conflict.

Each problem of the mining industry is local, but the fundamental issues of mining in the relevant format are international in nature.

Sustainable mining is a theoretical and highly unlikely goal to achieve. Metals and minerals are non-renewable resources, and their use can only be sustainable if consumption declines, and the rate of decline is going to be greater than the rate of depletion. From a practical perspective, achieving sustainability in the mining industry is a distant prospect, but many mining companies and industry associations are moving towards more economically, environmentally and socially responsible business practices.

Mining invariably benefits people and harms the environment. At the stages of their extraction and processing, numerous environmental problems arise.

First of all, during the extraction and processing of minerals, a large geological cycle is disrupted, in which various systems are involved. As a result, there is a great impact on the ecology of the mining region, and such an impact has negative consequences.

Impact of mining on the lithosphere [1]

1. The development of deposits of dense rocks is accompanied by significant extraction of forested and agricultural lands. Mining leads to significant changes in the landscape: the creation of anthropogenic forms of meso-relief – quarries, dumps.
2. Possible activation of geological processes (karst, landslides, scree, subsidence and displacement of rocks). During underground mining, subsidence pits and sinkholes are formed.
3. Mechanical disturbance of soils and their chemical pollution.

Impact of mining on the atmosphere [1, 2]:
As a result of the processes of primary processing of mined ores, large volumes of mine methane, sulfur, and carbon are emitted into the air. In addition, a large amount of dust enters the air during mining. When 1,000 tons of explosives are used, about 40 million m^3 of atmospheric air is polluted, exceeding the limit of permissible concentrations tenfold, and its spread is possible over 15 km. As a result of mass explosions in quarries, from 0.027 to 0.170 kg of dust is formed per 1 m^3 of rock.

Every day, up to two kilograms of dust falls on the territory adjacent to the quarries, as a result, the soil remains buried under a half-meter layer for many years, and often forever, and, accordingly, loses its fertility.

It should also be noted the negative impact and composition of explosives used in open pit development. Harmful gases produced as a result of the explosion are released into the air for 10–15 hours [2].

Impact of mining on the hydrosphere
The development of mineral deposits by an open method causes not only the degradation of the earth's surface in the area of mining operations, but also a sharp change in hydrological and hydrogeological conditions, which lead to a change in the quality of surface and underground waters [1]. As a result of the extraction of natural raw materials, reservoirs and underground waters are depleted, swamps are drained.

Surface waters suffer from pollution as a result of mineral extraction and processing. As in the atmosphere, a large amount of salts, metals, toxic substances, and wastes get into the water. As a result, microorganisms living in water bodies and fish die. If people use polluted water for their economic needs and for food, it leads to deterioration of the health of the population.

2. Methods

Assessment of the ecological situation of a certain region or the entire country is an urgent task today [3]. Environmental risk has an important place in the environmental assessment of the current or projected situation. Environmental risk – at all levels: from local to global – assessment of the likelihood of negative changes in the environment caused by anthropogenic or other influences. It is important to note that any economic activity always has an environmental risk.

There are four main directions in risk assessment: engineering, modeling, expert and social. In the modeling direction, mathematical models of processes that lead to undesirable consequences for humans and the environment when using harmful chemicals and compounds are developed.

The theory of probability and the means of mathematical statistics are used for the quantitative analysis of environmental risk. A peculiarity of the assessment of environmental risks is their dynamism, that is, there is a need to monitor the state of the environment as a whole and its individual components.

For water bodies, ecological risk is the probability of undesirable consequences in water ecosystems and their components as a result of anthropogenic and natural factors, including a decrease in water quality. Several methods of ecological risk assessment have been developed and used both for individual regions and river basins, as well as for certain sections of rivers subject to anthropogenic pressure.

This study used the method of environmental risk assessment [4] according to the formulas:

$$Risk = -\ln(P), \tag{1}$$

where:

$$P = \frac{\sum_i n_i}{N}, \tag{2}$$

where:

$$\sum_i n_i = \sum_i \frac{C_i}{TLV}, \tag{3}$$

where C_i is the concentration of the different pollutant (DP) that exceeds the threshold limit value (TLV) [5]; N is the total number of DP analyzed (content greater than TLV and less).

3. Results

The results of hydrochemical observations on the territory of the Northern GOK (Kryvyi Rih), which were conducted by the State Enterprise "Ukrchormetgeology", were used to assess the environmental risk.

The water objects of the natural-technogenic complex of Northern GOK include the tailings storage facility and the section of the Saksahan river, ponds and man-made water objects (figure 1).

The Northern GOK tailings pond has been in operation since 1963. The main dam of the Northern GOK tailings pond is located at a distance of 2.5 km from the mouth of the Petrykov creek, which flows into the Saksahan River. Also, in Petrykov creek along the outer contour of the right-bank enclosing dam, tailings, two emergency tanks were created: the first – in the western part and the second – in the northern part of the tailings. The area of the tailings pond is 1295 ha (of which the tailings pond itself is 980.0 ha, the circulating water pond is 315.0 ha). The length of the tailings pond is 17.3 km (tailings pond – 11.0 km, circulating water pond – 6.3 km). The contour of the tailings pond is closed by a 1.2 km long dividing dam, which separates the circulating water supply pond from the tailings pond itself. In addition to sludge pulp, quarry water (2.5 million m^3 / year), mineralization mine water (5.5 million m^3 / year), wastewater from treatment plants (36.15 thousand m^3 / year), and precipitation are discharged into the tailings pond, and surface filtration waters that were made from drainage systems built around the storage [6].

Preliminary studies have established that a persistent geochemical and hydrochemical anomalies has formed on the territory of the Northern GOK.

The center of the anomalies is a tailings, which pond's water has an elevated content of microcomponents: lead, cadmium, vanadium, bromine [6]. The content of some microcomponents also has an increased in the water of the river Saksahan and in the water of the pond Nedayvoda.

The results of the ecological risk calculations of water bodies on the territory of the Northern GOK are presented in figure 2.

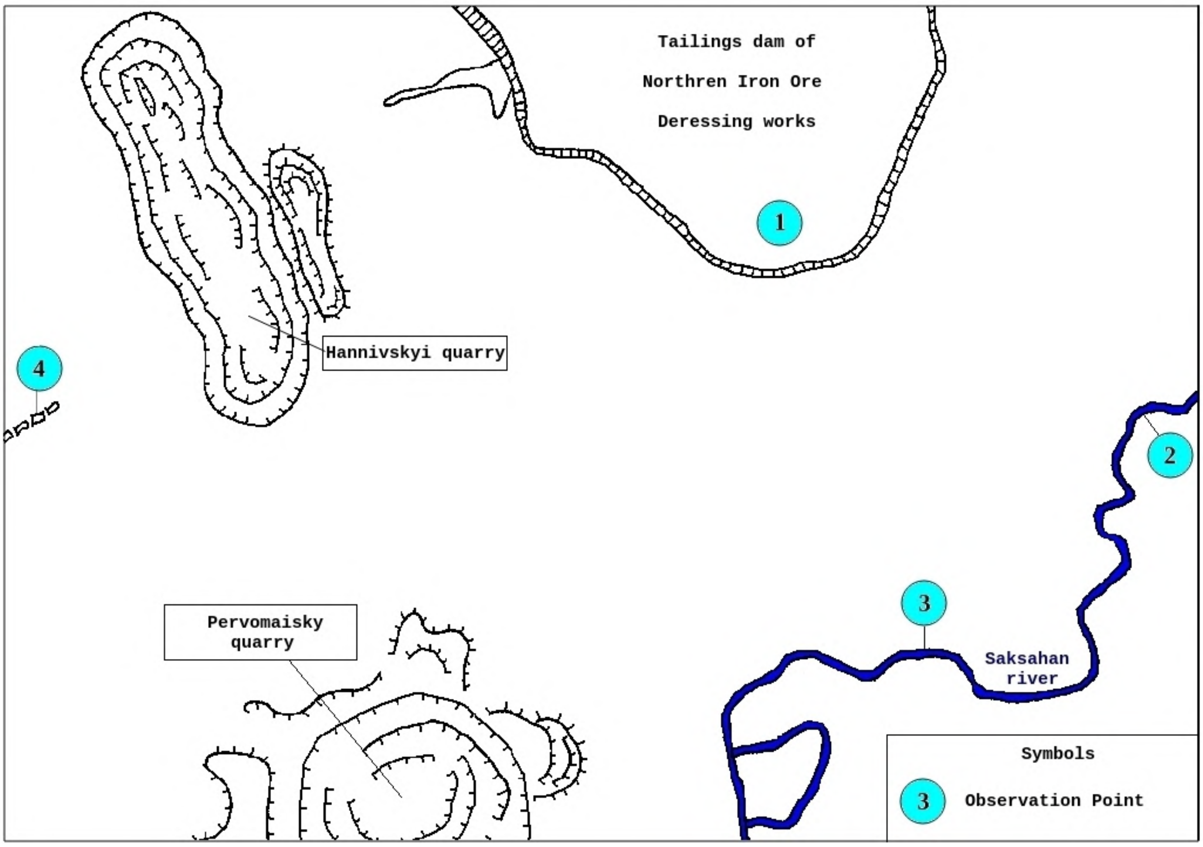

Figure 1. Map of Northern Iron Ore Dressing Works in Kryvbas with observation points for chemical composition of water (downstream) № 1 – Tailings dam NorthernIron Ore Dressing Works; № 2 – the first water meter post, the Saksahan River; № 3 – the second water meter post, the Saksahan River; № 4 – pond in the beam Nedaivoda.

According to the results of the calculations, it can be concluded that in general the ecological situation in the water bodies of the Northern GOK is deteriorating. The greatest concern is the too high content of bromine, both in the water of the tailings pond and in the water of water bodies. Let me remind you that bromine belongs to the second class of danger [5]. Bromine is a chemical element that is energetically accumulated by plants, animals in landscapes [7]. An excess of bromine in the human body leads to a decrease in the concentration of iodine in the hormones of the thyroid gland (hyperthyroidism), and also contributes to the rapid release of chloride ions by the kidneys.

The main symptoms of excess bromine are: memory impairment, insomnia, skin rashes, indigestion, bronchitis, rhinitis, as well as possible neurological disorders. Since this trace element is considered a very poisonous substance, the ingestion of a large amount of it into the human body causes serious consequences, even fatal. [8]

As mentioned earlier [6], the main source of bromine in the tailings pond is mine water. Among the heavy metals, an increased content of lead and vanadium is always noted, which enter the water of the tailings pond and the water of surface water bodies from the enrichment tails.

Among the studied natural and man-made water bodies, the greatest ecological risk is noted in the tailings stogare (-2.53) as of 05/04/2020. It should be noted that over time the ecological risk increases in the tailings stogare and in the pond Nedayvoda. In the Saksahan River, changes

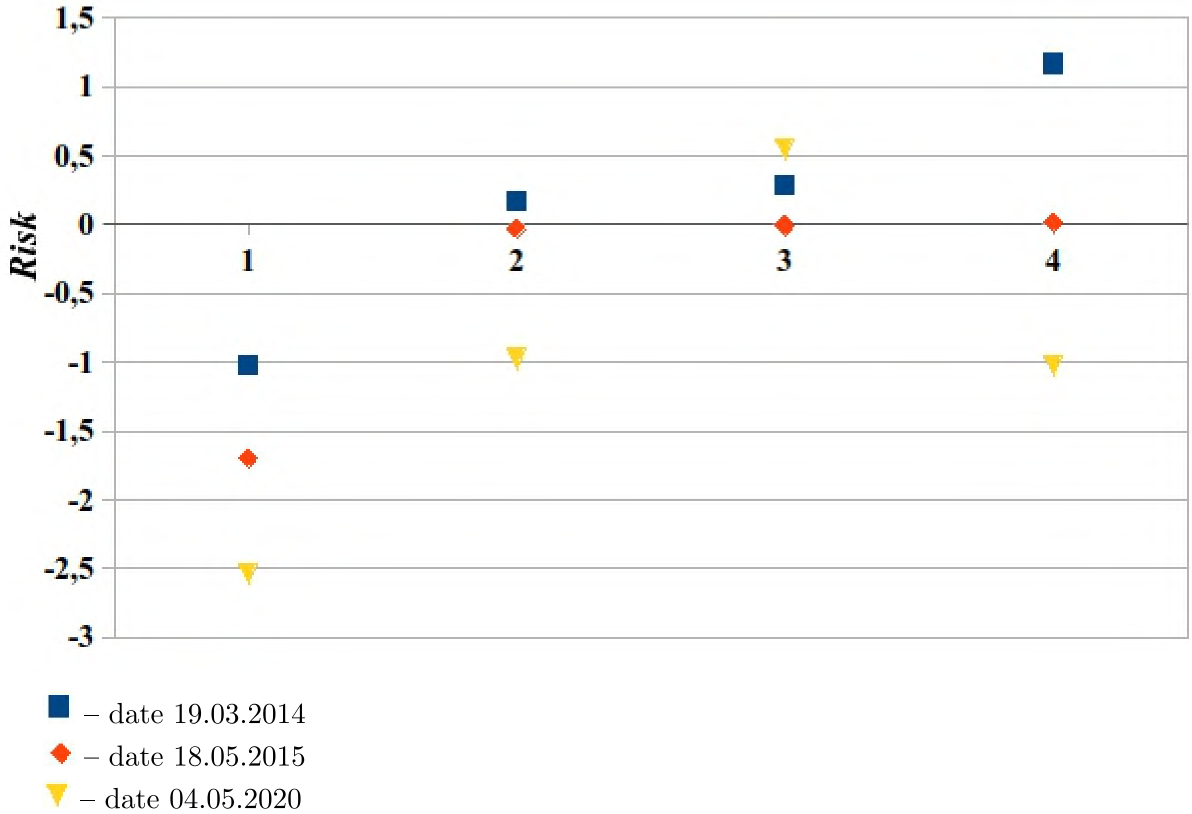

Figure 2. Environmental risk schedule for water bodies on the territory of the Northern GOK by observation points: 1 – Tailings dam Northern Iron Ore Dressing Works; 2 – the first water meter post, the Saksahan River; 3 – the second water meter post, the Saksahan River; 4 – pond in the beam Nedaivoda (2014, 2015, 2020).

in environmental risk values over time do not have a clear dependence. This is due to the fact that the hydrochemical regime of the river is formed under the influence of not only man-made but also natural factors.

It should also be noted that information for assessing the environmental situation in Kryvbas is not publicly available. This is also noted in the report [9, 10] and is a significant drawback of mining and blasting enterprises. Thus, the Metinvest company received zero marks for the Hannivskyi and Pervotravnev quarries, as it did not provide evidence to verify the information or did not provide information at all. Therefore, in order to achieve world standards in the field of mineral extraction according to the criteria of sustainable development, Ukrainian companies still need to pay a lot of attention to the issues of openness of information about nature protection in all main directions: protection and rational use of land, atmosphere, water resources, subsoil, managing of production waste.

4. Conclusions

The mining industry has a significant effect on the ecological state of water bodies, which is confirmed by the calculated value of ecological risk. It was determined that the water of the tailings storage has the greatest environmental risk (-2.53 on 05/04/2020), the Saksagan River (0.17 on 03/19/2014) has the lowest. The magnitude of ecological risk increases over time in almost all water bodies. The proposed method of calculating environmental risk for water bodies

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can be used to analyze the effectiveness of environmental protection measures and sustainable development of mining areas.

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References
[1] Mirzayev G, Ivanov B and Shherbakov V 1991 *Ekologiya gornogo proizvodstva [Ecology of mining]* (Moscow: Nedra)
[2] Savosko V 2016 *Heavy metals in soils at Kryvbas* (Kryvyi Rih: Dionat) URL https://doi.org/10.31812/0564/482
[3] Gadetska Z M and Kuzmych N V 2015 *Efektyvna ekonomika* (12) URL http://www.economy.nayka.com.ua/?op=1&z=4679
[4] Balachuk V I, Mokin V B and Iashcholt A R 2013 *Scientific works of Vinnytsia National Technical University* (1) 1–8 URL https://trudy.vntu.edu.ua/index.php/trudy/article/view/374/374
[5] Ministry of Health of Ukraine 2022 Hihiienichni normatyvy yakosti vody u vodnykh obiektakh dlia zadovolennia pytnykh, pobutovykh ta inshykh potreb naselennia [Hygienic standards for water quality in water bodies to meet drinking, household and other needs of the population] URL https://zakon.rada.gov.ua/laws/show/z0524-22#Text
[6] Khilchevskyi V and Sherstiuk N 2021 *Journal of Geology, Geography and Geoecology* **30**(3) 470–479 URL https://doi.org/10.15421/112143
[7] Perelman O and Kasymov N 1999 *Heokhymyia landshafta [Landscape geochemistry]* (Moskva: Yzdatelstvo Moskovskoho hosudarstvennoho unyversyteta)
[8] Levitin Y Y and Roi I D 2010 Brom *Farmatsevtychna entsyklopediia [Pharmaceutical encyclopedia]* ed Chernykh V P (Kyiv: MORION) 2nd ed ISBN 978-966-2066-34-0 URL https://www.pharmencyclopedia.com.ua/article/1980/brom
[9] EnerhoTransparentnist 2021 Shcho take vidpovidalnyi vydobutok v naskilky vidpovidalnymy ye ukrainski pidpryiemstva zalizorudnoi haluzi [What is responsible mining and how responsible are ukrainian enterprises in the iron ore industry] URL https://tinyurl.com/2r55mkut
[10] 2020 RMI Report 2020 Summary report Responsible Mining Foundation URL https://2020.responsibleminingindex.org/resources/RMI_Report_2020-Summary_RU.pdf

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Innovative technologies for organizing a balanced development of the business ecosystem (in the example of agriculture in Ukraine)

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Abstract. An increase in the population and an increase in the negative impact on the environment requires a review of the business organization model. Particular attention is paid to agriculture, which faces the task of solving the food problem on a global scale. At the same time, this industry is one of the leading polluters of the environment. The analysis of statistical data proves the low level of value added that is created in agriculture. The proposed agribusiness ecosystem model allows for a balanced development of agriculture and related industries based on four areas: economic, social, environmental, and innovative. Innovative solutions for all participants in the business ecosystem are based on the transition to a circular economy model using Industry 4.0 tools at all levels of system management: raw material suppliers, agricultural manufacturers, processors, customers, and government.

1. Introduction

A significant increase in the population, industrial and agricultural production, the use of vehicles, and other factors in recent decades have affected the deterioration of the environment, the increase in social and environmental problems, etc. In particular, agriculture is faced with the important task of solving the food problem. According to Agritech Tomorrow [1], population growth and food demand require an increase in crop production of at least 23% to meet the current standard of living.

Traditional production methods and technologies used in this industry cause the aggravation of such global problems of humanity as pollution of the atmosphere and hydrosphere, land degradation, and destruction of biodiversity [2]. Over the last decade, there has been a reduction in the world's forest cover by a third, a significant loss of biodiversity. The rate of growth in the volume of freshwater use exceeds the rate of population growth. There is a high level of soil pollution due to the intensive use of chemical fertilizers and synthetic pesticides. According to experts, about a quarter of global soils have undergone degradation [3]. In addition, agriculture and land use lead to more than 30% of global greenhouse gas emissions that cause climate change [4]. The war in Ukraine has not only socio-economic but also large-scale environmental consequences. Today, there are a number of studies on possible options for the ecological reconstruction of our country [5]. The problem of revising the system of production organization and business processes requires an immediate search for solutions. Since agriculture makes up a significant share of Ukraine's GDP, it is important to introduce innovative methods of organizing production processes in this industry. The European Union has adopted the Green Deal [6], which contains a number of requirements and obligations for manufacturers to comply with the transition to a circular economy model. In contrast to the traditional linear economy, the circular economy involves a closed cycle regarding production, consumption, and recycling, thus reducing the amount of resource consumption, waste, and emissions. Since Ukrainian agricultural enterprises supply a significant part of their products to EU countries, they must comply with the requirements of this agreement and reorient their organizational chains. In turn, this requires the introduction of innovative technologies and management methods to ensure the balanced development of agriculture and related sectors of the national economy.

2. Literature review

The rationale for the need to move from a linear to a circular economy model has been actively considered in the scientific literature in recent years [7–9]. The transition to a circular economy will help keep the value of resources and products at a high level, as well as minimize the production of waste. Government policies of different states based on public-private partnerships to implement the 3R (reduce, reuse, and recycle) model will help improve the efficiency of natural resource use and take a step forward toward achieving sustainable development goals [10].

The need to build supply chains based on the principles of a circular economy is substantiated in [11]. The authors prove that, despite the various external problems that affect the adoption of a particular decision of each company, the inclusion of a transition strategy to a circular economy allows companies to provide environmental advantages in the competition. The relevance of finding ways to solve environmental problems is substantiated in [12, 13], where the authors proposed a number of innovative solutions to solve this problem. At the same time, ensuring a balanced development of society requires taking into account not only environmental factors when building a model for further development [14]. Both when working in the domestic market of the country, and when entering foreign markets, it is necessary to take into account the social factor. In [15], a team of scientists proved the strengthening of social capital and the promotion of responsible research and innovation when a company enters the international level.

The transition to a circular economy, taking into account social indicators, contributes to the formation of the company's reputation and efficiency, and also allows it to enter the so-called circle of charity. At the same time, the existence of a gap between theoretical approaches and practical aspects of the implementation of the circular economy model is noted by scientists in the study []. A conscious choice is needed for all participants in the economic system in the transition to a circular economy, which will ensure their cooperation in a more holistic way. When defining the basic principles of the circular economy, some scientists distinguish between 3R (reduce, reuse, and recycle) [10], 4R (reduce, repair, remanufacture and recycle) [] or 5R (rethink, reduce, reuse, repair, recycle) [16, 17]. The development of innovative technologies allows the introduction of new tools to achieve the principles of a circular economy. In particular, work [18] examines the expected contributions of the introduction of Industry 4.0 tools for the implementation of the circular economy model. For an effective transition to a circular economy model, it is advisable to understand the essence of this process and the interests of all participants: government, suppliers, consumers, international organizations, etc [19].

The purpose of this study is to improve the scientific and methodological foundations for the implementation of the circular economy model based on the ecosystem approach, taking into account the innovative solutions of Industry 4.0.

3. Application of a systematic approach to creating a sectoral economy

Population growth increases the urgency of finding ways to solve the food problem of mankind. Ukraine is one of the key suppliers of agricultural products on the world market. Moreover, in recent decades, there has been a clear trend of reorientation of our state from industrial to agrarian (figure 1).

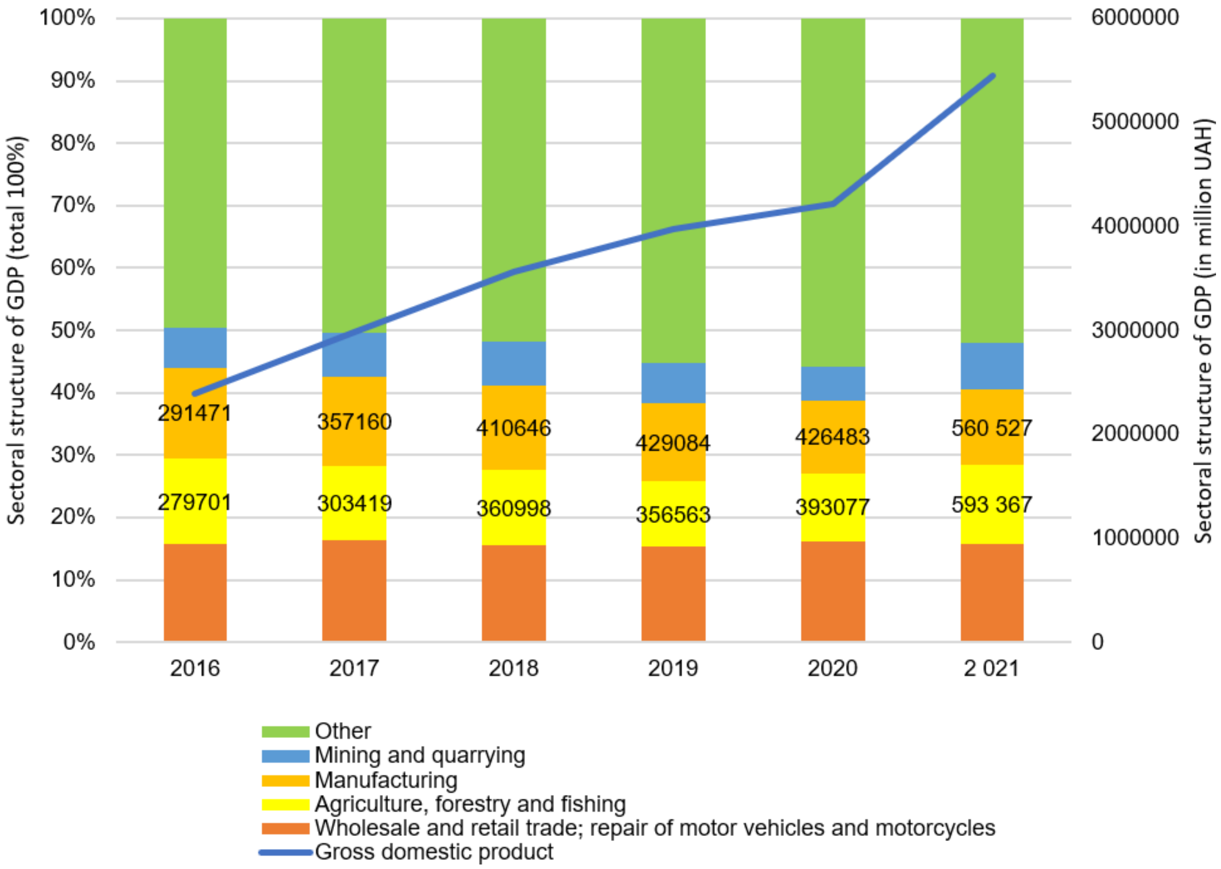

Figure 1. Structure of Ukraine's GDP, 2016 – 2021 (according to [20]).

As seen in figure 1, the share of agriculture is growing and is 10% of GDP in 2021. In turn, the share of the processing industry is gradually declining.

Comparing the share of agriculture in the country's GDP with European countries, this indicator is higher in Ukraine, and it is also higher than the world average (figure 2).

The problem of domestic agriculture is the low value added. For comparison, in European countries, the added value is several times higher (figure 3). In 2019, value added per worker in Ukraine amounted to USD 4,888 against USD 25,476 in European countries.

Value added is determined by the amount of value added at each stage of production, which increases its consumer properties. The added value is determined by the added value of the goods (products), which is formed in the process of procurement, processing, storage, and sale of products at the enterprise [23]. Thus, value added includes labor costs, depreciation, taxes, and profits. The low level of value added in the country indicates a low level of processing of input raw materials (materials), as a rule, is associated with a low level of science intensity of the industry.

In agriculture, value added is created by growing plants or animals. Technologies used in domestic agriculture have a relatively low level of innovation. Leading European countries have a significantly higher level of the added value of agricultural products due to the introduction of an integrated approach, namely: not primary raw materials, but processed products are sold, including for export. Thus, by developing the processing industry within the country, the state

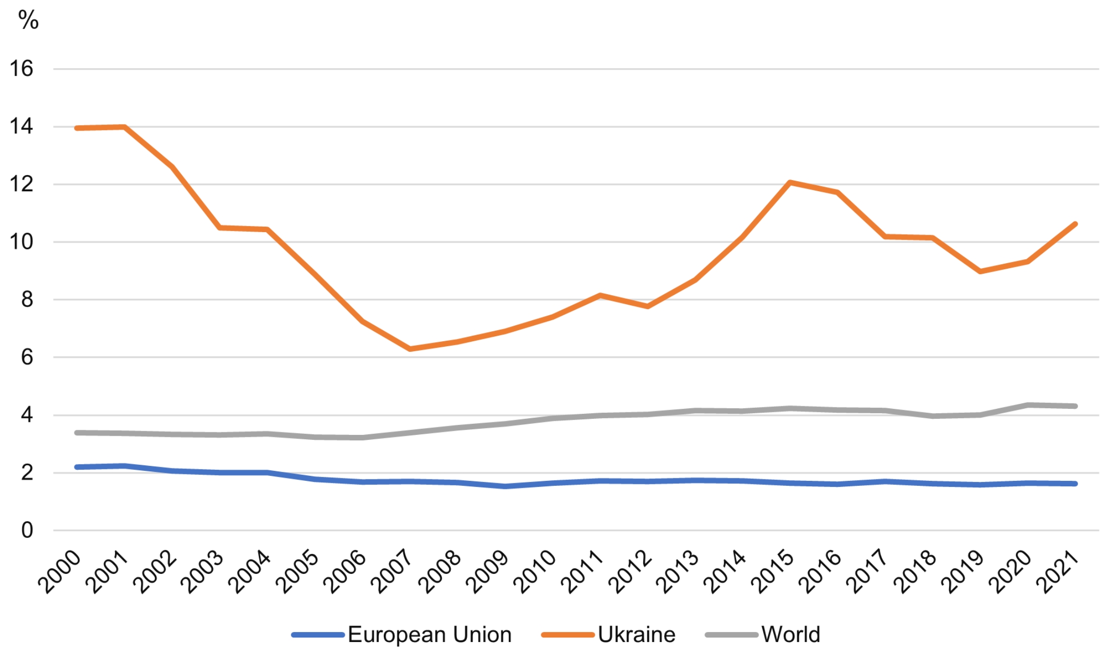

Figure 2. The share of agriculture in the country's GDP, 2000 – 2021 (according to [21]).

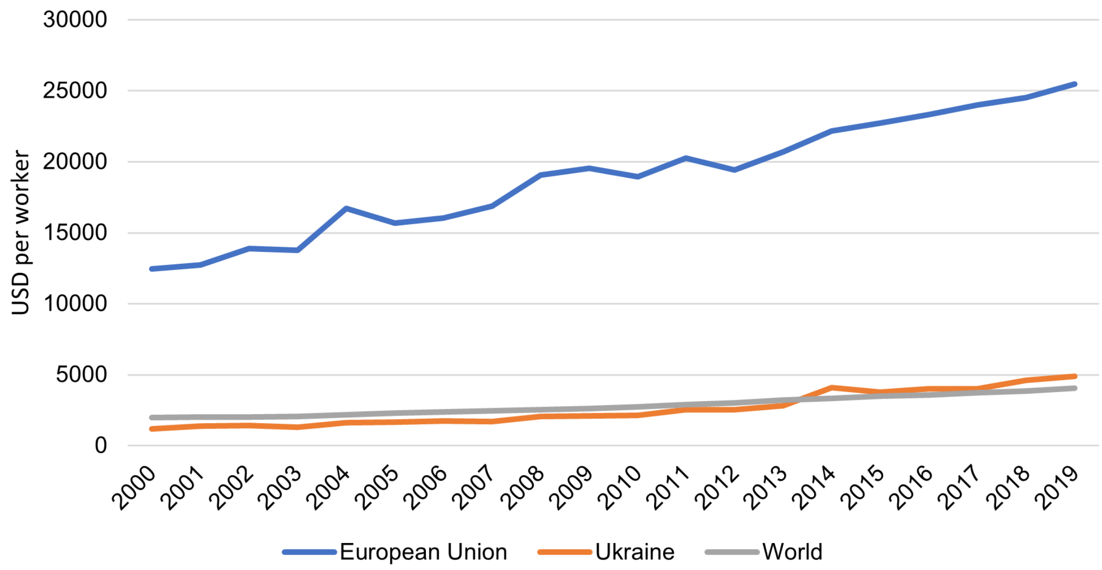

Figure 3. Agriculture, forestry, and fishing, value added per worker (constant 2015 USD) (according to [22]).

simultaneously stimulates the growth of the share of value added of the corresponding products (sector of the economy). To increase the level of the added value of domestic products, we consider it expedient to support the development of processing industries, which will allow us to reorient the country's economy from a supplier of raw materials to foreign markets to a supplier of finished products. This applies not only to agriculture but also to other industries, including metallurgy, which is the main exporter in Ukraine. At the same time, it is necessary to apply a systematic approach to building a sectoral economy. In the conditions of a circular economy, which provides for coordinated supply chains, sectoral relationships should be clearly built, taking into account the purely economic interests of individual economic agents, and taking into account the general economic effect. This approach will simultaneously reduce the country's import dependence since domestic manufacturers will come to replace foreign suppliers of the same household goods. This is especially true at the time of the post-war recovery of the Ukrainian economy.

4. An ecosystem approach for organizing a model of a circular economy on the example of agriculture

A feature of the introduction of the circular economy model in agriculture is not only individual steps to close the circle (processing of consumer waste), but the possibility of involvement in mutual supplies at the stage of production and use. To implement a circular economy in the agricultural sector, it is proposed to use an ecosystem approach. For the first time, the concept of an ecosystem in the economy was introduced by Moore, who proposed considering a company not as a separate economic player in the market, but as an element of a business ecosystem that takes into account several industries [24]. To date, there are various approaches to determining the essence and characteristics of a business ecosystem, taking into account the type of activity, its scale, and management methods. In the course of the study, an ecosystem agribusiness model was developed (figure 4), which includes both direct producers of agricultural products and resource suppliers, consumers, and other economic agents.

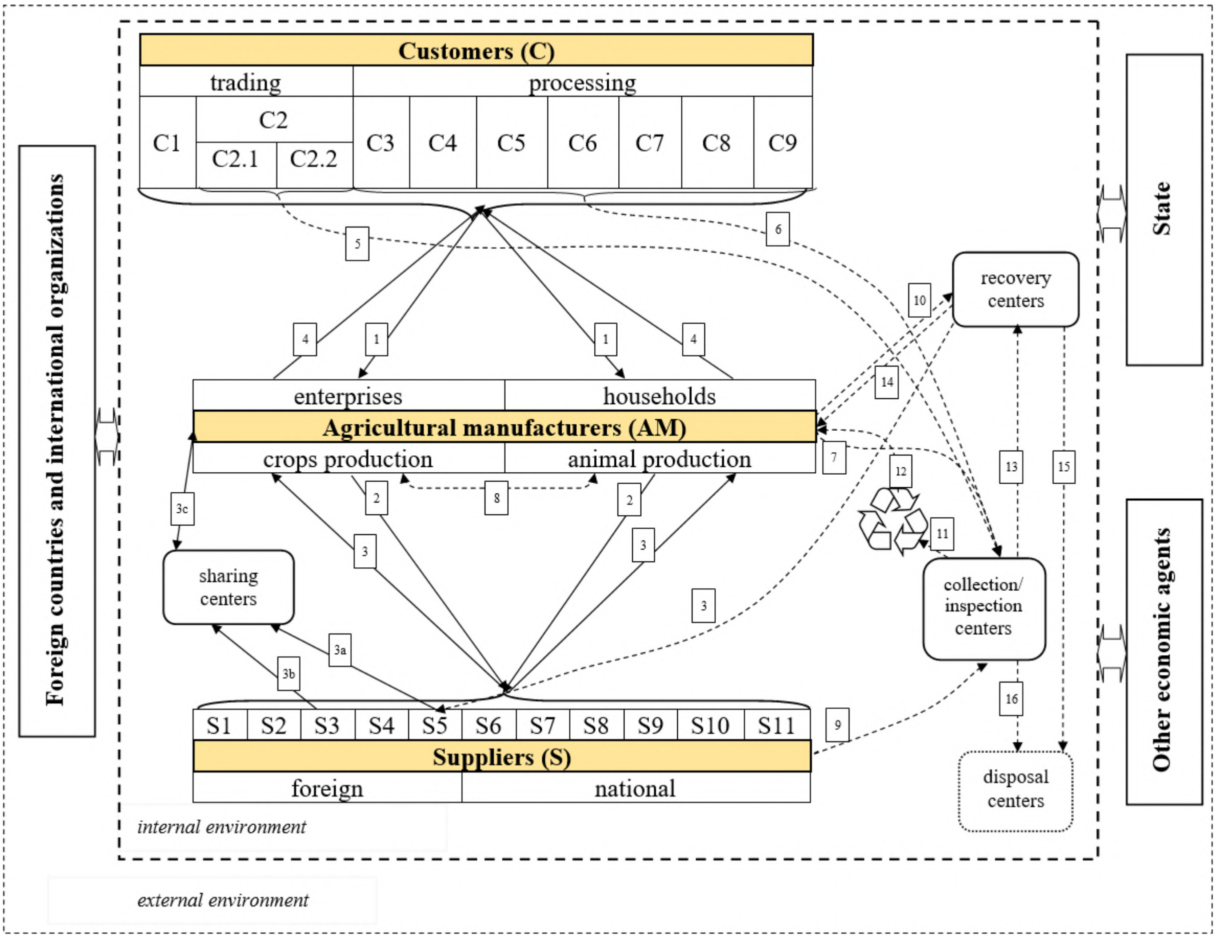

Figure 4. Agribusiness ecosystem model based on the circular economy (based on [25]).

Based on the degree of manageability and influence on the final result, we propose to distinguish between the internal and external environment of the agribusiness ecosystem. The internal environment should include elements that directly interact with each other in the process of creating added value. In particular, the internal environment of the agribusiness ecosystem built on the principles of a circular economy includes the main participants – Customers (C), Agricultural manufacturers (AM), and Suppliers (S), as well as additional, further contributing to the implementation of the circular economy model in the ecosystem – sharing centers, recovery centers, collection/ inspection centers, located centers. Depending on the purpose of the acquisition, Customers (C) are divided into two types – trade and processing. Sales of agricultural products can be carried out on external markets C1 (export) and on the domestic market C2 through intermediaries C2.1 (trade networks, retail trade) and directly to end consumers C2.2. The processing sector is also included among the consumers of agricultural products, namely: manufacturers of food, beverages, tobacco products (C3), manufacturers of textiles, clothing, leather products (C4), wood products, paper, printing (C5), manufacturers of chemicals (C6), pharmaceutical manufacturers (C7), furniture manufacturers (C8), biofuel producers (C9). Agricultural manufacturers (AM), depending on the form of business organization, are divided into legal entities and households, in accordance with the legislation of Ukraine. Farms can also be registered as legal entities or individuals. As a rule, household farms include family farming, producing products for themselves, and the surplus can be sold on the market. Depending on the type of products produced, agriculture is also divided into crop production and animal husbandry. Suppliers (S) of agricultural resources, which can be national or foreign. Depending on the type of resource, suppliers are divided into the following groups: melioration (S1), technologies (S2), land S3), personnel (S4), machinery (S5), fertilizers (S5), plant protection products (S6), breeding (S7), packaging (S8), feed (S9), veterinary drugs (S10). As in any system, there are certain relationships between its elements. As seen in figure 4, customers show demand for agricultural products (arrows 1). After analyzing the demand for products, agricultural producers will determine the demand for the inputs which they need for production (arrows 2). Depending on the cost of the resource, the period of its use, and the use of its financial capabilities, agricultural producers buy them (arrow 3), lease them, or share them. In particular, according to the basics of the circular economy, users can not only buy but also rent or share the necessary non-current assets. For agricultural producers, such assets are machinery, equipment, and land. Sharing centers act as an intermediary between the supplier of these resources and agricultural manufacturers (arrows 3a, 3b, 3c). According to experts, this type of service in agriculture is expected to grow in the coming years (figure 5).

Next, the production process is carried out using the necessary resources, and the products are sold to customers (arrows 4). Depending on the type of agricultural product, the production cycle can last for different times, for example, when growing plants, trees, and animals. The transition to environmentally friendly, organic production using the circular economy model makes it possible to almost completely eliminate waste to be disposed of at all stages. In particular, waste generated at the stage of selling finished products to end consumers, for example, spoiled or expired products (arrow 5) or processors of agricultural raw materials, such as production waste or unused raw materials and related products (arrow 6), fall into collection/inspection centers. Also, waste generated by agricultural producers can be directly redistributed between different producers. Crop waste can be used as animal feed. Also, animal waste can be used as fertilizer for crop production (arrow 8). Some scientists propose to apply the concept of mixed crop and livestock production, that is, a combination of two types of activities within one production unit – crop production and animal husbandry. The use of local feed and manure instead of imported and chemical fertilizers, for example, can help reduce agricultural CO_2 emissions [3]. The rest of the agricultural manufacturers' waste will be transferred to collection/inspection centers for further sorting (arrow 7). Waste generated during the supply

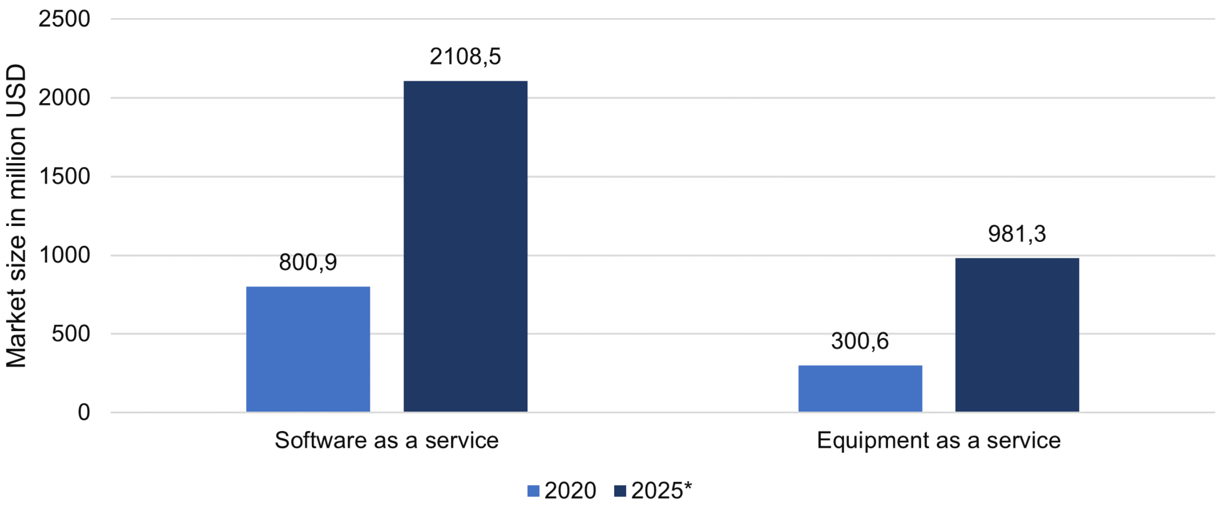

Figure 5. Size of the agriculture technology-as-a-service market in 2020 and 2025, by service type (in million USD) [26].

of resources to agricultural manufacturers (spoiled during transportation and delivery) will also fall into the collection/inspection centers (arrow 9). National suppliers (S) and agricultural processing (C3 – C9) are also mutual suppliers to each other through waste processing. The task of collection/inspection centers is to sort waste with subsequent distribution for processing (arrow 11) and recovery – for equipment and other components of the production process (arrows 10 and 13) with subsequent launch into production (arrows 12 and 14). For example, crop and livestock waste can be used as raw materials for some types of production (in the production of biofuels, textiles, furniture production, etc.). Thus, a much smaller volume is sent to the located centers (arrows 15 and 16).

All elements of the agribusiness ecosystem interact with external actors. The external environment of the agribusiness ecosystem includes state institutions, partners in foreign countries, international organizations and governments of other countries. The state, as a regulatory body, also influences the development of the agribusiness ecosystem (through the development of legal documents, regulations, the provision of permits, etc.). On the other hand, the state can act as a supplier and client through the activities of state enterprises and organizations, that is, acting as a component of the internal environment. In order not to complicate the logical chains of relationships between the participants in the agribusiness ecosystem, figure 4 does not display the settlement flows between them. For effective management of the agribusiness ecosystem, we consider it expedient to use the CATWOE method [27, 28]. This method is one of the tools for solving system management problems. The name of the method comes from the abbreviation: Customers – Actors – Transformation – Worldview – Owners – Environmental constraints, meaning key variables. As part of the agribusiness ecosystem, these components will be:

- Customers – stakeholders related to the product created by the system (customers, customers, end users);
- Actors – stakeholders directly involved in the processes (manufacturers, processors, intermediaries);
- Transformation is a business process that includes the processing process (production of agricultural products, their processing, waste processing processes, repair work, etc.);
- Worldview – a systematic vision of the problem and its potential solution with a preliminary

assessment of the consequences and future prospects (a preliminary assessment of the feasibility of making a decision based on a balanced assessment in four areas: economic, environmental, social, and innovative);

- Owners – stakeholders who are most interested in solving the problem and have the authority to allocate resources for transformation (government bodies, business owners, investors, etc.);
- Environmental constraints – factors or conditions external to the solution of the problem that affects the implementation of the decision (market capacity, legal requirements, international conditions, environmental risk factors, etc.).

By analyzing the impact of each component of the CATWOE analysis, it is possible to maintain optimal conditions for the functioning of the agribusiness ecosystem as a single organism.

5. Innovative tools for balanced business ecosystem development

Circular agriculture was widely practiced in pre-industrial societies. At the same time, due to the industrialization of production, it was gradually pushed aside by the modern model of organizing production processes in this industry, which made it possible to significantly increase its economic efficiency through the widespread use of chemical fertilizers, mechanization, and automation, specialization in growing monocultures, etc. This approach, as we know, has led to negative environmental consequences. Long-term consequences of the negative impact on the environment and humans will be felt for a long time [7].

The development of modern technologies and the application of an ecosystem approach to the organization of business processes in the agricultural sector will ensure decent economic results while maintaining a balanced development. By balanced development, we mean a balance between four components: economic, environmental, social, and innovative. These development vectors should be basic for all participants in the agribusiness ecosystem. According to the concept [29], sustainable development involves taking into account three components: economic, social, and environmental. However, at present, given the rapid development of innovations, in particular, in the era of Industry 4.0, information and communication technologies can significantly optimize business processes, including the agricultural sector [25,30]. Innovations are new and (or) improved competitive technologies, products, or services, as well as organizational and technical solutions [31]. Innovations occur at all stages of interaction between participants in the agribusiness ecosystem: from the stage of supplying resources to the stage of final processing or waste disposal. When taking into account the innovative component, it is important to use a systematic approach, since the agricultural products themselves contain a relatively low degree of innovation, compared with the products of knowledge-intensive sectors of the economy. At the same time, innovative solutions of an individual participant in the business ecosystem will bring a synergistic effect in related industries and at adjacent levels of interaction between participants.

Innovative solutions that will contribute to the effectiveness of the agribusiness ecosystem can occur at three stages: the development (selection) of agricultural products, the production (cultivation) of agricultural products, the consumption and processing of waste, business processes and products of related industries that are part of the agribusiness ecosystem. To improve the performance of the agribusiness ecosystem, we consider it expedient to implement the following measures [1, 3]:

Agricultural manufacturers:

- Mixed farming (mixed farming) – a combination within the same agricultural producer of crop and livestock, which will reduce the amount of waste from each of the individual types of production, as well as mutually provide the necessary resources.

- Shift from mono-crop agriculture to growing a set of interrelated crops, where the cultivation of some creates favourable conditions for others on the same land, which will improve the quality and fertility of the land without the use of chemicals.
- Agroforestry – planting trees in combination with crops or pastures that will help restore biodiversity in agricultural landscapes, increasing soil fertility by increasing the accumulation of organic matter from decaying nature.
- Water recycling and wastewater use – recycling and reuse of irrigation water in agriculture. According to experts, the use of wastewater in agriculture can irrigate an additional 40 million hectares, or 15 percent of all irrigated land [3].
- The use of innovative technologies in crop production – bee vectorization technologies, indoor vertical farming using hydroponics, aeroponics, micro-drip irrigation, laser scarecrows to scare away birds and rodents, the use of minichromosomal technologies without the use of genetically modified products that have allergic and others, etc.) for organic farming.
- Implementation of innovative technologies of Industry 4.0 – precision farming based on Big Data processing, remote sensing, the use of aircraft, robotics, and automation to improve the condition of plants and optimize resources, increase productivity; automated dairy plants, automated cleaning systems, automated feeders, and non-antibiotic treatment of animals with acoustic impulses, as well as the application of robotics, artificial intelligence for animal welfare and agricultural productivity; introduction of real-time kinematic technology (RTK) to reduce soil damage by machinery. Experts estimate that the market value of precision farming will grow from about 7 billion USD in 2021 to 14,5 billion USD by 2027 [32]. The size of the global smart farming market will grow from approximately 12,4 billion USD in 2020 to 34,1 billion USD by 2026 [26].
- Registration on international platforms and promotion of the national manufacturer in the international market.
- Application of modern management methods based on the analysis of world experience and advanced technologies (automation of production and management operations with a combination of agricultural machinery, computer systems, electronics, chemical sensors and data management into a single system in order to improve equipment operation and decision-making, reduce human impact and errors).

Intermediate and end users:

- Transition to responsible consumption of resources, providing for the reduction of food waste, waste sorting, preference for organic products to stimulate and materially support organic production.

Government:

- State support for organic production and the use of new technologies (drip irrigation, precision farming, rainwater harvesting, crop productivity, closed water cycle, green energy, etc.) by providing subsidies, tax incentives, concessional lending, etc.
- Stimulating the development of processing industries operating on domestic raw materials.

Suppliers:

- Development of new varieties and hybrids of plants and animal breeds, strains of microorganisms, brands and modifications of agricultural machinery, technology, chemical and biological preparations (vaccines).
- Development and implementation of new technologies and new types of machinery and equipment.

The innovative smart agriculture approach to agribusiness, which is actively spreading around the world, is based on the use of technologies and solutions of the Internet of Things, which improves operational efficiency, increases yields, and minimizes costs through processing realtime data, their analysis and the use of digital production management systems.

Smart agriculture is introducing a range of programs and digital solutions such as precision farming, variable rate technology, irrigation, and smart greenhouses. Today, precision farming has become the most important innovative agricultural direction in the developed countries of the world. Other promising areas in smart farming include: variable speed technology (VRT), unmanned drones, soil monitoring systems, and precision animal husbandry. The main factors driving the need for the transition from agribusiness to smart agriculture are the current realities of climate change, the need to conserve water and other types of resources, and a focus on improving efficiency through cost optimization [33]. Given the trends, the agricultural sector is the driving force behind the innovative development of the national economy.

6. Conclusions

The application of the proposed concept of agribusiness ecosystem will allow to obtain a synergistic effect in related industries, which, within the framework of this development, will provide the agricultural sector with raw materials, machinery, and other resources. Such an approach will help to increase the level of value added created with the participation of agriculture. Separation of the internal and external environment allows all participants in the business ecosystem to minimize the risks and threats to their own business, reducing the degree of dependence on external influences.

The proposed approach to the formation of a model for a balanced development of a business ecosystem is to take into account four areas of development: economic, environmental, social, and innovative. Taking into account the innovative component of development at all levels of ecosystem management makes it possible to take into account the potential for further development, as well as to balance the interests of all participants. This approach contributes to the optimization of economic results at the system level, while reducing the negative impact on the environment. The innovative technologies of Industry 4.0 reduce economic costs and conquer the consumption of resources, providing the maximum return on them, taking into account the supply chains within the ecosystem.

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References

[1] Mass Challenge 2023 Agriculture Innovation: 10 Tech Trends to Watch in 2023 URL https://masschallenge.org/articles/agriculture-innovation/
[2] United Nations 2021 Global Issues URL https://www.un.org/en/global-issues
[3] Circular agriculture for sustainable rural development UN/DESA Policy Brief 105 United Nations Department of Economic and Social Affairs URL https://www.un.org/development/desa/dpad/wp-content/uploads/sites/45/publication/PB_105.pdf
[4] 2021 *World Social Report 2021: Reconsidering Rural Development* (United Nations publication) URL http://www.un.org/development/desa/dspd/wp-content/uploads/sites/22/2021/05/World-Social-Report-2021_web_FINAL.pdf
[5] 2022 Environmental impacts of the war in Ukraine and prospects for a green reconstruction URL https://www.oecd.org/ukraine-hub/policy-responses/environmental-impacts-of-the-war-in-ukraine-and-prospects-for-a-green-reconstruction-9e86d691/
[6] 2019 A European Green Deal URL https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en
[7] Zeng X, Ogunseitan O A, Nakamura S, Suh S, Kral U, Li J and Geng Y 2022 *Circular Economy* **1**(1) 100003 ISSN 2773-1677 URL https://doi.org/10.1016/j.cec.2022.100003

[8] Barreiro-Gen M and Lozano R 2020 *Business Strategy and the Environment* **29**(8) 3484–3494 URL https://doi.org/10.1002/bse.2590
[9] Dieckmann E, Sheldrick L, Tennant M, Myers R and Cheeseman C 2020 *Sustainability* **12**(5) 1725 ISSN 2071-1050 URL https://doi.org/10.3390/su12051725
[10] Khajuria A, Atienza V A, Chavanich S, Henning W, Islam I, Kral U, Liu M, Liu X, Murthy I K, Oyedotun T D T, Verma P, Xu G, Zeng X and Li J 2022 *Circular Economy* **1**(1) 100001 ISSN 2773-1677 URL https://doi.org/10.1016/j.cec.2022.100001
[11] Abbate S, Centobelli P, Cerchione R, Giardino G and Passaro R 2023 *Journal of Cleaner Production* **385** 135665 ISSN 0959-6526 URL https://doi.org/10.1016/j.jclepro.2022.135665
[12] Zabulonov Y L, Popov O O, Iatsyshyn A V, Iatsyshyn A V, Puhach O V and Stokolos M O 2022 *IOP Conference Series: Earth and Environmental Science* **1049**(1) 012013 URL https://doi.org/10.1088/1755-1315/1049/1/012013
[13] Wang R, Usman M, Radulescu M, Cifuentes-Faura J and Balsalobre-Lorente D 2023 *Gondwana Research* **119** 138–152 ISSN 1342-937X URL https://doi.org/10.1016/j.gr.2023.02.023
[14] Ivanov R V, Grynko T V, Porokhnya V M, Pavlov R A and Golovkova L S 2022 *IOP Conference Series: Earth and Environmental Science* **1049**(1) 012041 URL https://doi.org/10.1088/1755-1315/1049/1/012041
[15] Castilla-Polo F and Sánchez-Hernández M I 2022 *Journal of Business Research* **152** 231–241 ISSN 0148-2963 URL https://doi.org/10.1016/j.jbusres.2022.07.038
[16] 2021 The 5 R's of sustainability and zero-waste management URL https://landfillsolutions.eu/the-5-rs-of-sustainability-and-zero-waste-management/
[17] Tserng H P, Chou C M and Chang Y T 2021 *Sustainability* **13**(2) 754 ISSN 2071-1050 URL https://doi.org/10.3390/su13020754
[18] Awan U, Sroufe R and Shahbaz M 2021 *Business Strategy and the Environment* **30**(4) 2038–2060 URL https://doi.org/10.1002/bse.2731
[19] Skorobogatova N 2022 Formation of Sustainable Development of Competitive Business in an Unstable Economy *2022 IEEE 3rd International Conference on System Analysis & Intelligent Computing (SAIC)* pp 1–6 URL https://ieeexplore.ieee.org/document/9922912
[20] State Statistics Service of Ukraine GDP production and distribution, by types of economic activity URL https://www.ukrstat.gov.ua/
[21] The World Bank Group 2023 Agriculture, forestry, and fishing, value added (% of GDP) URL https://data.worldbank.org/indicator/NV.AGR.TOTL.ZS
[22] The World Bank Group 2023 Agriculture, forestry, and fishing, value added per worker (constant 2015 US$) URL https://data.worldbank.org/indicator/NV.AGR.EMPL.KD
[23] Kordalska A and Olczyk M 2023 *Economic Systems Research* **35**(2) 265–291 URL https://doi.org/10.1080/09535314.2022.2047011
[24] Moore J F 1993 *Harvard Business Review* (May-June) 75–86 URL http://web.archive.org/web/20230331054114if_/https://blogs.harvard.edu/jim/files/2010/04/Predators-and-Prey.pdf
[25] Skorobogatova N 2022 *Technology audit and production reserves* **2**(4(64)) 6–10 URL https://doi.org/10.15587/2706-5448.2022.256610
[26] Statista 2023 Size of the agriculture technology-as-a-service market in 2020 and 2025, by service type (in million U.S. dollars) URL https://www.statista.com/statistics/1092149/agriculture-technology-as-a-service-market-by-service-type/
[27] Xing K, Ness D and ren Lin F 2013 *Journal of Cleaner Production* **43** 93–102 ISSN 0959-6526 URL https://doi.org/10.1016/j.jclepro.2012.11.052
[28] Nattassha R, Handayati Y, Simatupang T M and Siallagan M 2020 *Agriculture & Food Security* **9**(1) 10 ISSN 2048-7010 URL https://doi.org/10.1186/s40066-020-00264-8
[29] International Institute for Sustainable Development 2022 Sustainable Development URL https://www.iisd.org/mission-and-goals/sustainable-development
[30] Voitko S, Gaidutskiy I and Skorobogatova N 2020 Industry 4.0 and next normality in ensuring sustainable development *2020 III International Conference on High Technology for Sustainable Development (HiTech)* pp 1–2 URL https://ieeexplore.ieee.org/document/9363981
[31] Verkhovna Rada of Ukraine 2022 On Innovative Activity URL https://zakon.rada.gov.ua/laws/show/40-15?lang=en#Text
[32] Statista 2023 Forecast market value of precision agriculture worldwide from 2021 to 2027 (in billion U.S. dollars) URL https://www.statista.com/statistics/721921/forecasted-market-value-of-precision-farming-worldwide/
[33] Kernasyuk Y and Haydenko O 2021 *Agribusiness today* URL http://agro-business.com.ua/agro/ekonomichnyi-hektar/item/21782-innovatsiina-ahrotekhnika-ta-tekhnolohii.html

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The influence of deep loosening on the ecological and meliorational state of drained mineral soils

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The influence of deep loosening on the ecological and meliorational state of drained mineral soils

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Abstract. The existing problems of energy, water, and food crises and climate changes determine the need to implement appropriate adaptive measures to improve the ecological and reclamation state of drained mineral soils. For the application of deep loosening of the soil as an adaptive agromelioration measure, a transition from traditional crack loosening of the soil and strip loosening of the soil to improved technologies of continuous layer-by-layer loosening of the soil based on energy-efficient and moisture-regulating principles is proposed. Their comparative evaluation according to the main indicators of overall efficiency was carried out on drained mineral soils of a representative object in the Western Polissia zone of Ukraine. According to the results of the evaluation of various technologies of deep soil loosening, it was determined that the technologies and technical means of continuous deep loosening of the soil have an advantage in all main indicators: agrotechnical, water-physical, energy, technological, ecological, and economic. In particular, the moisture availability of the soil increased by 27 % due to better accumulation of atmospheric precipitation, the yield of cultivated crops also increased by 20-30 %, and the aftereffect period increased to 4 years. This is a cost-effective and investment-friendly adaptive measure to ensure a satisfactory ecological and reclamation state of drained mineral soils (with an investment payback of 1 year). This provides modern principles of adaptive land use in changing climatic conditions and can be an effective alternative to expensive reconstruction and modernization of existing drainage systems.

1. Introduction

The current problems of energy, water, and food crises, as well as climate changes, determine the need to implement appropriate adaptive measures to improve the ecological and reclamation state of drained mineral soils.

In the zone of drainage reclamation, this is possible based on the development of a complex of adaptive, including agro-reclamation, measures. They are aimed at effective regulation of the water regime, regulation and accumulation of moisture in the soil profile and within the system, and improvement of technologies, and means of deep soil loosening according to energy-efficient and resource-saving principles. This will make it possible to effectively accumulate moisture in the soil profile and on the massif to be drained, to increase its moisture supply [1].

2. Analysis of previous studies

The positive aspects of using deep loosening as an effective agromelioration measure on sod-podzolic soils in the Western region of Ukraine have been shown in many studies. At the same time, it was noted the presence of negative agroecological and man-made components of impact on the soil by technical means for its implementation [1].

Some functional advantages of applying deep layer-by-layer loosening on over-moistened mineral soils using strip technology were noted and used by Kozhushko based on the developments of Kravets regarding a trenchless multi-tier soil loosener [2].

Depending on the hydrological, soil, and other conditions, continuous, strip, or crack loosening (cracking) is traditionally considered and used [1].

Traditional deep loosening of drained soils using slit or strip technologies is used only as an auxiliary measure to increase the efficiency of drainage using deep looseners mainly of the riser type. At the same time, only local influence is actually carried out on the active part of the soil massif (the active root layer and the aeration zone of the drained soil) with the formation of vertical filtration channels for the intensification of drainage of surface runoff. This really contributes to the strengthening of the technological effect on drainage, but at the same time, it strengthens the washing water regime in the soil, which over time leads to the impoverishment of the fertile layer and causes a negative ecological effect.

At the same time, the designs of traditional deep looseners actually perform rather coarse loosening, which does not provide the necessary quality of soil structure in accordance with agrotechnical recommendations. They compact the soil of the walls of the incised cracks, require significant energy expenditure during loosening, and have insufficient loosening completeness and the duration of its aftereffect [3].

Therefore, the use of deep loosening as an effective adaptive measure is restrained by the imperfection of existing technologies and means that do not provide the necessary quality and effectiveness of loosening in accordance with modern conditions and requirements.

Research methodology. For a comparative evaluation of the effectiveness of the application of various variants of deep loosening of drained mineral soils on a representative object for the conditions of the Western Polissia of Ukraine, experimental studies were carried out using the main methods of the general theory of the experiment (analytical, experimental and statistical), mathematical modeling and a machining experiment using modern information and computer technologies.

According to the obtained experimental results, predictive calculations were made based on the use of an appropriate complex of forecasting and simulation models, which includes a local climate model, models of the water regime and water regulation technologies of drained lands, a model of the development and formation of the crop of cultivated crops, which are implemented on the basis of a long-term forecast [4].

For an approximate assessment of the ecological sustainability of the researched measures, the degree of consideration of the factors of ecological reliability of their operation and to maintain favorable natural and reclamation and soil regimes within the project term, the calculation of the coefficient of ecological reliability (k_n) of the operation of the reclamation system was carried out based on the set of relevant physical indicators of ecological efficiency (indicators water regime, indicators of salt regime and productivity of drained lands). The ecologically optimal option is considered to be the one for which the coefficient of ecological reliability is in the interval of values $k_n = 0.5...1.0$, in addition, the coefficient of ecological reliability indirectly reflects the ecological and melioration state of drained mineral soils [4].

3. Research results

On the basis of the generalization of existing and our research, we scientifically substantiated the need and possibility through improved energy-efficient and moisture-regulating technologies and technical means of deep loosening to influence the improvement of the technical, technological, and economic efficiency of the use of drained mineral soils.

Deep loosening changes the macrostructure of drained mineral soils and affects the macroaggregate state of soils, their density and porosity, water-physical properties, and, accordingly, the ecological and melioration state of drained mineral soils and the conditions for the development of cultivated crops and productivity (figure 1).

To ensure the implementation of the necessary improvement of deep loosening for modern conditions and requirements, a transition from the traditional widely used crack and strip loosening technologies to continuous layer-by-layer deep loosening of the soil differentiated by depth is proposed. This soil loosening method has been improved according to energy-efficient and moisture-regulating principles, and according to tiered technical means [5].

The improved technology and means of deep continuous loosening make it possible to improve the structure of the soil, which is developed in each horizon, layer by layer. At the same time, it makes it possible to differentiate the value of its loosening by a depth of up to 0.6 m.

Implementation of continuous deep loosening with mechanical reformatting of the macroaggregate and granulometric composition of the soil massif with its layer-by-layer distribution according to agrotechnical recommendations affects the water-physical properties of the soil. It is also decisive for the technological and physical prerequisites for the creation of favorable water-air and natural-ameliorative regimes, and, therefore, the provision of the necessary economic and ecological effects [1].

The formation of a granular and fine-grained structure makes it possible to effectively use the moisture-accumulating potential of the soil. This is done by the formation of a large surface area of soil particles and small gaps between them in the zone above the plow sole, where the root systems of most agricultural crops are potentially located.

The formation of a large- and medium-granular structure to the depth of the drainage makes it possible to quickly remove excess fluid. This excess is removed through the increased gaps between soil particles and simultaneously accumulates in the soil due to the formation of a sufficient surface area of soil particles. The formation of a medium-granular structure in the upper quarter of the upper layer protects the accumulated moisture from excessive evaporation from the surface and weathering.

As a result, a moisture-accumulating structure is obtained in each of the soil layers. This structure is appropriate for the purpose of each layer: with maximum moisture accumulation potential in the upper part of the soil and sufficient water permeability with simultaneous moisture accumulation in the lower part of the soil profile.

The proposed design of the deep loosener for improved loosening is a frame with bearing risers. Soil-loosening working bodies are attached to them in the form of the conjugation of a plowshare with a concave arrow-shaped soil-loosening element of variable curvature. The shape and parameters of the surface of this element determine the necessary deformation, stress, and, therefore, crushing of the soil layer. The general layout of the deep loosener is determined by the spatial distribution of the soil-loosening working bodies in three perpendicular directions (figure 2) [6].

Comparative field production tests of various technologies and means of deep loosening were performed at the facility of the Private Agricultural Enterprise "Myrne" in the Kostopil district of the Rivne region (Ukraine) on an area of 25 hectares [6].

Soil conditions: sod-podzolic clayey sandy soils with a content of physical sand in the arable horizon of 58.3 % (0...20 cm) and in the subsoil layer – 79.8%, with a filtration coefficient of the arable horizon – 0.13... 0.4 m/day, and at a depth of 20 cm or more – 0.13...0.003 m/day.

Depth of laying drainage – 0.8...1.2 m; the distance between the drains is 10...20 m.

The study of the influence of various technologies and deep loosening means on the water-physical properties and agro-melioration state of drained mineral soils was solved by conducting

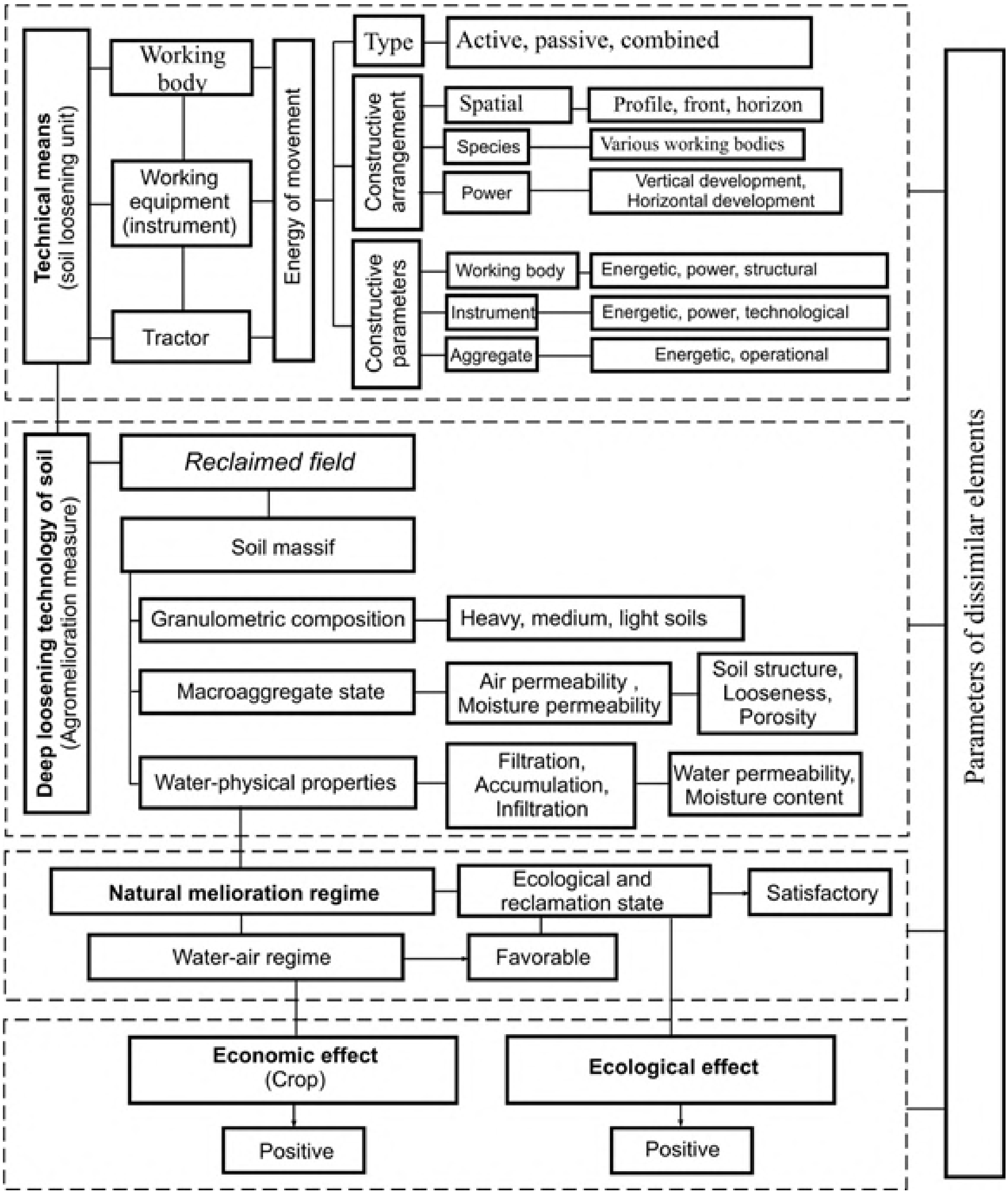

Figure 1. Structural and hierarchical scheme of the necessary principles of improving technologies and technical means of deep loosening of draining mineral soils based on consideration of the interaction between the parameters of heterogeneous elements.

comparative production tests according to the following options: 1 – crevice loosening of the soil; 2 – band loosening of the soil; 3 – improved continuous loosening of the soil; 4 – control option without soil loosening.

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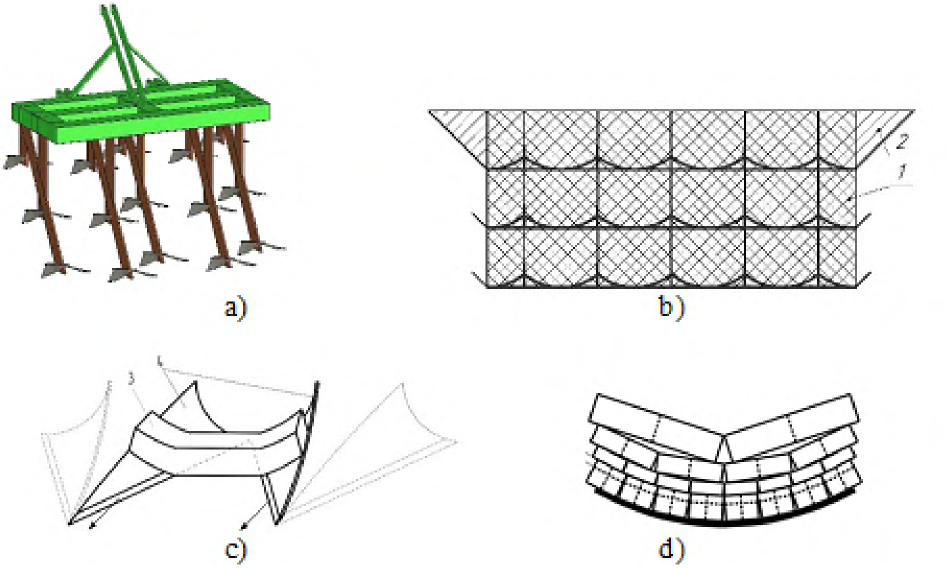

Figure 2. Tiered deep loosener: a) – construction, b) – loosening of the cross profile of the soil; c) – action on the element of the soil layer, d) – the principle of soil grinding; 1 – structural loosening; 2 – loosening by chipping; 3 – soil layer; 4 – working bodies.

The indicator of the quality of soil loosening was determined in the form of the coefficient of completeness of loosening. It was reduced to the volume of soil on an area of 1 hectare (100×100 m) with a power of 1 m for the objectivity of the assessment by different loosening technologies.

Table 1 presents a generalized comparative characteristic of the values of the main indicators of water-physical properties in the 0.6 m soil layer averaged over time (by the after-effect period) and plane (by the soil profile) and by different types and variants of its loosening.

Table 1. Comparative characteristics of the water-physical properties of the 0.6 m soil layer according to loosening options.

Variants of soil loosening	Soil density[1] γ, t/m^3	Soil cracking[1] A, %	Soil water permeability[1] k_f, t/day
Without soil loosening	1.45	42.2	0.12
Crack soil loosening	1.41 (0.04 t/m^3 /2, 9%)[2]	46.1 (3.9%/9.2%)[2]	0.25 (0.13 t/day /206%)[2]
Strip soil loosening	1.32 (0.13 t/m^3 /8.9%)[2]	47.3 (5.1%/12%)[2]	0.36 (0.24 t/day /296%)[2]
Continuous soil loosening	1.15 (0.30 t/m^3 /21%)[2]	54.9 (12.7%/30%)[2]	0.53 (0.41 t/day /443%)[2]

[1] absolute value, [2] deviation from control

The term of effective technological aftereffect of the considered methods of deep loosening of drained mineral soil was: crevice soil loosening – 1 year; strip soil loosening – 3 years, continuous soil loosening – up to 4 years.

Table 2 presents a generalized comparative characteristic of the averaged values of the main agromelioration indicators of a layer of loosened soil of 0.6 m with a change in the supply of productive moisture and according to the most universal indicator of the productivity of cultivated crops for variants of its loosening.

The best results of deep loosening of mineral soils are achieved when using continuous

Table 2. Comparative characteristics of the main agromelioration indicators of the 0.6 m soil layer according to loosening options.

Variants of soil loosening	Productive moisture reserve [1] Wh, m^3/ha	Productivity of crops according to the coefficient of efficiency [1] PAR, %
Without soil loosening	316	0.80
Crack soil loosening	594 (278 m^3/ha /49.0%)[2]	0.88 (0.08%/10.0%)[2]
Strip soil loosening	655 (339 m^3/ha /51.0%)[2]	0.99 (0.19%/24.0%)[2]
Continuous soil loosening	711 (395 m^3/ha /55.5%)[2]	1.16 (0.36%/45.0%)[2]

[1] absolute value, [2] deviation from control

loosening based on the use of a multi-layer deep loosener. At the same time, the density of the soil in the arable soil layer decreased to 1.1...1.15 t/m^3, and in the sub-arable soil layer – to 1.2...1.3 t/m^3. In addition, the possibility of predicting and obtaining the structure in any horizon of the vertical profile of loosened soil due to the possibility of adjusting the parameters of the working body of the deep loosener was proven. At the same time, unlike other technologies, the optimal structure of loosened soil was achieved: in the arable layer, 55...60% by weight of soil aggregates with a diameter of 10...50 mm; the remaining 40% – by the total weight of aggregates with a diameter of less than 10 mm and greater than 50 mm, and in the sub-arable horizon with a diameter of 20...50 mm – 70...80%, and in total aggregates with a diameter of less than 20 mm and larger than 50 mm – 20 ... 30%.

According to research results, deep loosening also has a positive effect on the temperature regime of the soil, especially the arable horizon, where when the air temperature increases, the maximum temperature in the loosened soil becomes lower than without loosening.

Under the action of deep loosening, the depth of soil freezing decreases by 8...12 cm, and thawing is accelerated by 2-3 days in the spring. This is especially characteristic of the first year after the effect.

Moisture evaporation is related to temperature and water conditions. Deep loosening, breaking the capillary connection in the upper horizons, reduces the intensity of capillary nutrition and, accordingly, reduces its evaporation from the soil surface.

According to [7], deep loosening can be a mechanism that contributes to reducing the evaporation of other greenhouse gases from the soil surface by stimulating their accumulation and absorption deep in the soil mass rather than in the upper soil layer. At the same time, loose soil macroaggregates with a diameter of 2...8 mm are characterized by 51% better-absorbing properties (over a total 20-day period) than soil macroaggregates with a diameter of up to 2 mm.

In addition, the deep loosening carried out accordingly will contribute to the translocation processes of moving soil organic carbon into the depth of the massif, which are one of the methods of its sequestration. The measured rates of carbon sequestration by the soil range from 50 to 1000 kg/ha/year. The global carbon sequestration potential is 0.9...10.3 Pg/year, which can offset from one quarter to one third of the annual increase in atmospheric carbon dioxide, which is 3.3 Pg/year. The cumulative potential of soil carbon sequestration for 25–50 years is 30–60 Pg [8, 9].

Table 3 shows the comparative efficiency of using different variants of deep loosening on drained mineral soils according to the results of field experiments.

The obtained results of the harvest of cultivated crops adequately describe the achieved indicator of the improvement of their growing conditions and ensure their increase on average

Table 3. Comparative effectiveness of deep loosening on drained mineral soils.

	Variants of soil loosening	Year of effect	Cultivated crops	Crop increment	Payback period, years
1	Crack soil loosening	1	sugar beets	13.1 c/ha / 4.5%	1
		2	winter cereals	1.8 c/ha / 6.1%	1
		3	spring cereals	1.4 c/ha / 5.3%	1
2	Strip soil loosening	1	sugar beets	51.6 c/ha / 18.1%	1
		2	winter cereals	4.6 c/ha / 15.9%	1
		3	spring cereals	2.5 c/ha / 9.4%	1
3	Continuous soil loosening	1	sugar beets	93.25 c/ha / 32.3%	1
		2	winter cereals	6.5 c/ha / 22.3%	1
		3	spring cereals	5.1 c/ha / 19.3%	1

according to the options of deep loosening of drained mineral soils: crevice loosening of the soil – 5...10%; strip loosening of the soil – 10...20%; continuous loosening of the soil (improved) – 20...35%.

The results of the analysis show that the method of continuous loosening of the soil provides a greater increase in the yield of cultivated crops than with crackted or strip loosening of the soil. This not only compensates for the cost of its implementation, but also creates a profit.

According to the results of predictive and simulation modeling using the appropriate set of models [4, 10], the effectiveness of the application of improved continuous loosening of the soil during the growing season was determined. This was carried out in combination with various methods of water regulation of drained mineral soils on the example of the studied object (soil – sandy loam, area – 10 ha, cultivated crop – perennial grasses for hay) for the estimated dry growing season under the conditions of heat and moisture supply (p = 70%).

Table 4 shows fragments of the generalized results according to the following options: 1 – preventive sluicing (PS); 2 – preventive sluicing with continuous deep loosening (PS+DL); 3 – preventive sluicing with continuous deep loosening with an aftereffect in 1 year (PS+DL+1 year); 4 – moisture sluicing (MS, subsoil moisturing).

The presented data show that the application of improved continuous loosening of drained mineral soils against the background of preventive sluicing in the estimated dry growing season increases the accumulation of precipitation by more than 90% and increases the moisture availability of the soil according to the $n(IW)$ indicator by 27%. At the same time, the positive effect is partially preserved after 1 year after the action with sufficient environmental reliability.

The efficiency of the technology of water regulation of drained lands (PS + DL) is similar to the moisturizing sluicing (MS, subsoil moistening) according to a set of technological and ecological indicators. At the same time, this method does not require additional costs of irrigation water for moistening the soil massif with lower material costs.

The summarized results of determining the economic efficiency of investments in the reconstruction and modernization of drainage systems using various technologies and means of deep loosening according to the appropriate methods and models [11] are presented in table 5.

The calculations performed to determine the comparative economic efficiency and investment evaluation of various options for deep loosening of drained mineral soils confirm the sufficient feasibility of their use in projects of reconstruction and modernization of drainage systems in the Western Polissia zone of Ukraine.

Thus, all considered technologies of deep loosening of the soil are profitable and economically beneficial. At the same time, the most technologically, economically, and ecologically effective

Table 4. Comparative characteristics of indicators of technological and environmental efficiency according to research options.

Options	WPh^0 m^3/ha	WP m^3/ha	$n(IW)$	OR m^3/ha	EF m^3/ha	K_y	Y_a c/ha	H m	k_r
PS	355	117	0.22	2937	3997	0.46	17.3	1.047	0.49
PS + DL	545	227	0.28	2957	4027	0.49	18.4	1.036	0.51
PS+DL+1y	420	136	0.22	2944	4038	0.48	17.8	1.043	0.5
MS	355	204	0.28	2934	4743	0.61	22.9	0.908	0.49
Change in the values of the indicators relative to the PS, %									
PS + DL	53.5	94.0	27.0	0.7	0.8	6.5	6.4	1.1	4.1
PS + DL + 1y	18.3	16.2	0.0	0.2	1.0	4.3	2.9	0.4	2.0

WPh^0 – productive moisture reserve in the calculated soil layer, m^3/ha; WP – weighted average productive moisture reserve in the estimated soil layer for the growing season, m^3/ha; $n(IW)$ the duration (part) of the optimal moisture supply of the estimated soil layer for the growing season; OR – amount of effective atmospheric precipitation during the growing season, m^3/ha; EF – value of the effective value of the total evaporation during the growing season, m^3/ha; K_y – crop yield reduction factor; Y_a – actual yield, c/ha; H – weighted average level of groundwater, m; k_r – the coefficient of ecological reliability.

Table 5. Comparative characteristics of indicators of technological and environmental efficiency according to research options.

	Indicator	Without soil loosening	Crack soil loosening	Strip soil loosening	Complete soil loosening
1	Profitability index	0.59	1.03	1.95	3.06
2	Net discounted profit, UAH/ha	-4908	377	11369	24708
3	Discounted payback period, $years$	-	27	9	5

is the improved continuous deep loosening of the soil.

The technology and means of deep continuous loosening of the soil, which has been improved according to energy-efficient and moisture-regulating principles, make it possible to improve the macrostructure of the active layer of drained mineral soils layer by layer to a sufficient depth. This is done in order to influence their water-physical properties, water, air, heat, and other ecological components of the natural-ameliorative regime of the soil massif, which is positively reflected in the conditions of the development of agricultural crops and their productivity.

4. Conclusion

According to the results of the evaluation of various technologies of deep soil loosening, it was determined that the technologies and technical means of continuous deep loosening of the soil have an advantage in all main indicators: agrotechnical, water-physical, energy, technological, ecological, and economic. In particular, the moisture availability of the soil increased by 27% due to better accumulation of atmospheric precipitation, the yield of cultivated crops also increased by 20-30%, and the aftereffect period increased to 4 years.

This is a cost-effective and investment-friendly adaptive measure to ensure a satisfactory ecological and reclamation state of drained mineral soils (with an investment payback of 1 year). This provides modern principles of adaptive land use in changing climatic conditions and can be an effective alternative to expensive reconstruction and modernization of existing drainage systems.

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References

[1] Stashuk V A and et al 2021 *Scientific and methodological recommendations for the creation and functioning of drainage systems in changing modern conditions* (Rivne: NUWEE)
[2] Kozhushko L 2001 *Improvement of drainage filters* (Rivne: NUWEE)
[3] Kravets S V, Skobliuk M P, Stino O V and Zoria R V 2018 *Critical-depth two-tier soil looseners* (Rivne: NUWEE)
[4] Romashchenko M I and et al 2010 *Scientific and practical aspects of optimization of water regulation of drained lands on ecological and economic grounds* (Rivne: NUWEE)
[5] Mazhayskiy Y, Rokochynskiy A, Lukianchuk O, Turcheniuk V, Volk P, Prykhodko N and Chernikova O 2019 Deep loosening as effective adaptive agromeliorative practice on drained mineral soil of European Polesie in variable climatic conditions *19th International Scientific Conference Engineering for Rural Development Proceedings. Jelgava, 20.-22.05.2020* pp 28–35 URL https://doi.org/10.22616/ERDev.2020.19.TF009
[6] Tkachuk V F and et al 2011 *Agromelioration multi-tier deep looseners* (Rivne: NUWEE)
[7] Chaplot V, Abdalla K, Alexis M, Bourennane H, Darboux F, Dlamini P, Everson C, Mchunu C, Muller-Nedebock D, Mutema M, Quenea K, Thenga H and Chivenge P 2015 *Agriculture, Ecosystems & Environment* **203** 110–118 ISSN 0167-8809 URL https://doi.org/10.1016/j.agee.2015.02.001
[8] Lal R 2004 *Geoderma* **123**(1-2) 1–20 URL https://doi.org/10.1016/j.geoderma.2004.01.032
[9] Havrysh V S and et al 2013 *Scientific and methodological recommendations for the use of deep loosening on drained mineral soils of the Western Polissia of Ukraine* (Rivne: NUWEE)
[10] Romashchenko M, Husyev Y, Shatkovskyi A, Saidak R, Yatsyuk M, Shevchenko A and Matiash T 2020 *Reclamation and water management* (1) 2–20 URL https://doi.org/10.31073/mivg202001-235
[11] Stashuk V A and et al 2013 *Provisional recommendations for the evaluation of investment projects for the construction and reconstruction of water management facilities and reclamation systems* (Rivne: NUWEE)

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Development of a scientific and methodological approach to assessing losses from warfare in natural ecosystems on the territory of Ukraine

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Development of a scientific and methodological approach to assessing losses from warfare in natural ecosystems on the territory of Ukraine

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Abstract. The assessment of the impact of hostilities on the environment remains an important issue for predicting changes resulting from military-technogenic activities and assessing the losses incurred by ecosystems in Ukraine. This article proposes an integrated approach for predicting the possible level of hostilities' impact by utilizing aggregated environmental information on ecosystem composition, indicators of military-technogenic load, organization of trophic networks in relevant biogeographic zones, and biodiversity composition. The concept of environmental safety of hostilities is introduced as a projection into the military technosphere of the ecosystem sustainability concept, where the target function is the conservation of the natural biota of operational zones and areas of hostilities. The article presents a block diagram of the procedure for assessing the state of ecosystems in war zones and proposes a classification of levels of military-technogenic disturbance of natural ecosystems based on the state of edifier sinusia.

1. Introduction

One of the unresolved problems in the field of military ecology is the development of appropriate methods for assessing the damage caused by warfare to natural ecosystems, which is one of the major issues in this field. In Ukraine, an undeclared war with the Russian Federation is ongoing in Polissya and the southeastern industrial regions (Donetsk, Dnipro, Zaporizhzhia, Luhansk, and Mykolaiv). This area is a technologically advanced and industrial region of Ukraine, where pollution of the environment through the conduct of hostilities (HS) and the possible defeat of potentially hazardous objects (PHO) is directly related to the formation of a military-technogenic load (MTL) as a result of the operation and combat use of weapons systems and military equipment at the facilities of industrial-urban agglomerations and on the territory of natural ecosystems.

To conduct a detailed environmental assessment of the impact of HS on natural ecosystems in the practice of forecasting in precision military ecology, it is necessary to determine the relative importance of military-anthropogenic factors influencing the environment, which have qualitative uncertainty, and evaluate the values of the parameters of the natural system, which have quantitative certainty. Today, it is necessary to determine the key factors influencing MTL from HS in natural ecosystems. Unfortunately, the current quantitative uncertainty in predicting the impact of MTL on the components of the ecosystem indicates that our knowledge and information resources are not yet sufficient to predict changes in natural ecosystems under the influence of HS in operational areas.

Recent studies have highlighted the importance of developing appropriate methods for assessing the impact of hostilities on the environment. For instance, studies [1, 2] focused on the environmental impact of military activities in Ukraine and proposed an approach for assessing the ecological status of the areas affected by military operations. Another study [3] evaluated the impact of military activities on the state of natural ecosystems in Ukraine and proposed a system for monitoring the environmental situation in the areas affected by military operations. Furthermore, studies [4, 5] examined the impact of military activities on the environment in Ukraine and proposed a set of measures to reduce the negative impact of military activities on the environment. These studies suggest that developing appropriate methods for assessing the impact of hostilities on the environment is crucial for mitigating the negative effects of military activities on natural ecosystems.

2. Related works

Comparative analysis of several publications on the assessment of anthropogenic changes in various types of ecosystems [1–4] allowed us to formulate the following methodological principles for assessing the MTL from warfare:

1. Differentiated consideration of the reaction of different ecosystems to the same impact of the MTL.
2. In each ecosystem, an artificial change in the environment of the abiotic environmental factors of the military natural-technogenic geosystem (MNTG), which has the greatest indication value, is adopted as criteria for assessing its changes.
3. Integral assessment of the level of MTL on land and ecosystems and in general is carried out in conditional indicators on an appropriate point scale based on an assessment of quantitative data on changes in individual components of ecosystems (for example, due to the ratio of affected and unmodified ecosystem areas).
4. The specificity of military ecosystems determines the development of methodological methods for assessing their ecological state.
5. From the point of view of the possibilities of using empirical data in the study of the system of interaction "military-anthropogenic influence – biota reaction" to predict the state of MNTG, the idea of regulating the effect on biota through its "critical link", which can be a group of species or even one indicator species, seems expedient.

The basis of a comprehensive environmental assessment of the state of natural ecosystems is a joint analysis of biotic and abiotic environment-forming factors that characterize ecosystems in conditions of dynamic military-technogenic load from HS. It is known that a biogeocenosis, ecosystem or biological community that has existed in unchanged form for a long time has a certain intrinsic ability to withstand perturbing natural influences. This ability of the ecological system is often called "resilience" or "stability" by biologists [6].

There is an approach based on trying to link the resilience of a community with some measurable characteristics of it. Among ecologists, it is considered almost an axiom that communities which are more complex in structure and richer in the number of species are more stable [7–10]. As a characteristic of community stability in biology, the information measure of diversity is most often used the Shannon and Simpson indices [11]. However, the direct use of indicators of species diversity as a criterion characterizing the sustainability of ecosystems makes sense only for communities that do not have a quantitative hierarchy. Therefore, in real biogeocenoses that have a pronounced hierarchical structure, the use of diversity indicators to quantify the measure of stability is hardly justified [12].

Recent research has focused on developing comprehensive assessment procedures to evaluate the impact of warfare on natural ecosystems. One such study proposed a methodology for assessing the ecological state of ecosystems in areas affected by military activities using the structural and functional organization of biotic communities [13]. The study emphasized the importance of considering the specific characteristics of different ecosystems and their responses to military-technogenic loads. Another studies proposed a methodological approach for assessing the impact includes both qualitative and quantitative indicators [5,14]. The study [5] highlighted the importance of analyzing changes in vegetation cover at different spatial scales to better understand the impact of military activities on natural ecosystems. The study [15] shows a tool to monitor environmental dynamics and plan military training activities, but its limitation lies in that the obtained values of the indicator vary and are subjective to the experts' knowledge and experience. Thus, further advancing this approach is needed by developing a scientific method to derive the weights of environmental variables.

The peculiarities of the above-mentioned areas of research on the development of a method for assessing losses for the territories of hostilities require the development of comprehensive assessment procedures, for the development of which it is necessary to have reliable environmental information about the components of the ecosystems of the territories of the operational zones of HS.

The purpose of the publication is to develop a comprehensive scientific and methodological approach to assessing losses in natural ecosystems due to the influence of MTL factors during hostilities in Ukraine. Recent research in this area has emphasized the need for a differentiated approach that considers the specific characteristics of different ecosystems and their responses to MTL. This approach should include both qualitative and quantitative indicators and analyze changes in ecosystems at different spatial scales to better understand the impact of military activities on natural ecosystems.

Military Training Areas (MTAs) cover at least 2 percent of the Earth's terrestrial surface. These areas are potentially important for biodiversity conservation. The greatest challenge in managing MTAs is balancing the disturbance associated with military training and environmental values. These challenges are unique as no other nature use is managed for these types of anthropogenic disturbances in a natural setting.

3. Results

It should be noted that almost all the existing approaches to assessing the sustainability of ecosystems have considered this problem in natural ecosystems in relation to natural extreme actions, which for a considerable period of time are familiar to these ecosystems and very rarely are complex. The problem of the stability of ecological systems to the military-technogenic impact of the HS looks completely different. Here dealing, as a rule, with actions that are not peculiar to the natural environment, and are a complex conglomerate of mechanical, physical and chemical factors, combined in different ratios when using certain means of destruction and military equipment on the battlefield.

An equally important circumstance is that when assessing the interaction of natural and MNTG, the stability of the ecosystem has a twofold meaning. On the one hand, the stability of the ecosystem is its property, which characterizes the ability to withstand external military-technogenic loads. But on the other hand, if some ecosystem is resistant to a specific military-technogenic factor, then this factor is safe for this ecosystem. Thus, the concept of environmental safety of hostilities is a projection into the military technosphere of the concept of ecosystem sustainability. Given that the target function in studying the interaction of the military technosphere and the biosphere is the level of preservation of the natural biota of operational zones and areas of HS, then both previously mentioned concepts are tied together through the achievement of these goal, but each of them has its own purpose.

The study of the sustainability of ecosystems should quantify the permissible, according to the conditions of ecosystem conservation, the level of militarytechnogenic load, and the study of causal relationships in the process of its formation should determine the technological ways to achieve a biologically determined threshold for each military-technogenic factor.

An indicator of natural equilibrium is the ability of natural ecosystems to develop with the achievement of reaching the maximum during cyclic succession. Maintaining a HS in an ecosystem changes its abiotic component, which, through the mechanism of homeostasis, influences certain species, usually suppressing them. Therefore, the ecosystem is out of balance and, according to the principle of Le Chatelier-Brown [16], its equilibrium shifts in the direction in which the effect of external action factors and HS weakens. In practice, this means a decrease in the number of species, that is, the degradation of the biocenosis to some new, equilibrium, but lower level. Determining the mechanism of homeostasis in the presence of external action of the HS for all levels of the organization of ecosystems is of great importance for predicting its behaviour at one level or another.

According to the general ideas of classical ecology [17, 18], the stability of ecosystems is associated not only with the very fact of preserving the species' composition but also with the ability to return to the primary equilibrium state after external actions [19]. Thus, with regard to the specifics of the HS, the ecosystem is resistant to MTL as long as its biota retains the ability for self-healing, that is, to return to the path of evolution according to the laws of cyclical succession after the removal of the MTL.

In order to determine the degree of MTL influence factors on the environment and to develop proposals for the decision-maker, a search and development of scientifically based models and indicators for the environmental classification of MTL factors from HS maintenance in operating areas is underway [20, 21]. During the study of the problems of environmental assessment of MTL, a number of issues arise related to the justification of the methodology for its implementation, which is specific to the field of military ecology [22, 23].

Due to the fact that in our time ecosystems are not purely natural, but naturalanthropogenic, it becomes necessary to isolate the factors of MTL in a whole group of other anthropogenic loads associated with industrial and agro-technical activities.

By projecting this condition into the military technosphere, its possible to formulate the concept of environmental safety for the operational zones of HS: hostilities are environmentally safe if the military-technogenic perturbation of the abiotic component of the ecosystem does not exceed the level at which its biota retains the ability to self-healing (that is, to return to the path of evolution according to the laws of cyclical succession after the removal of the MTL).

Thus, the stability of the ecosystem, as the ability to withstand military-technogenic pressure with a limited duration of validity (limited terms of HS), is nothing more than a biologically justified measure of the value of MTL, which, when using various types and systems of weapons and military equipment, makes combat operations environmentally safe.

But earlier it has already been emphasized that any biological restriction can perform regulatory functions in relation to the military technosphere only when it has a quantitative assessment. Therefore, in general, the requirements that must be met by a biologically significant criterion limiting the level of influence of the militarytechnogenic load on the ecosystem is as follows:

- *complexity* – the ability to integrally characterize military-technogenic changes in the natural ecosystem;
- *objectivity* – the possibility of determining on the basis of real natural parameters the state of the natural ecosystem;

- *concreteness* – the presence of the numerical value of the corresponding indicator;
- *purposefulness* – the application of the criterion should ensure the preservation of the natural ecosystem.

For an integral assessment, an ecosystem approach can be applied when there is a whole edifier sinusia or trophic network of vertebrates observed in this territory as an indicator [24, 25].

To form the basic prerequisites for the development of a comprehensive procedure for ecosystem indication of the state of the natural environment of the HS area, will limit ourselves to considering the balance equations of terrestrial ecosystems of military facilities, which are based on the laws of mass and energy storage and describe the mass-energy exchange between the main biotic components of the ecosystem: producers (P), substrates (S) and consumers (Q) (figure 1).

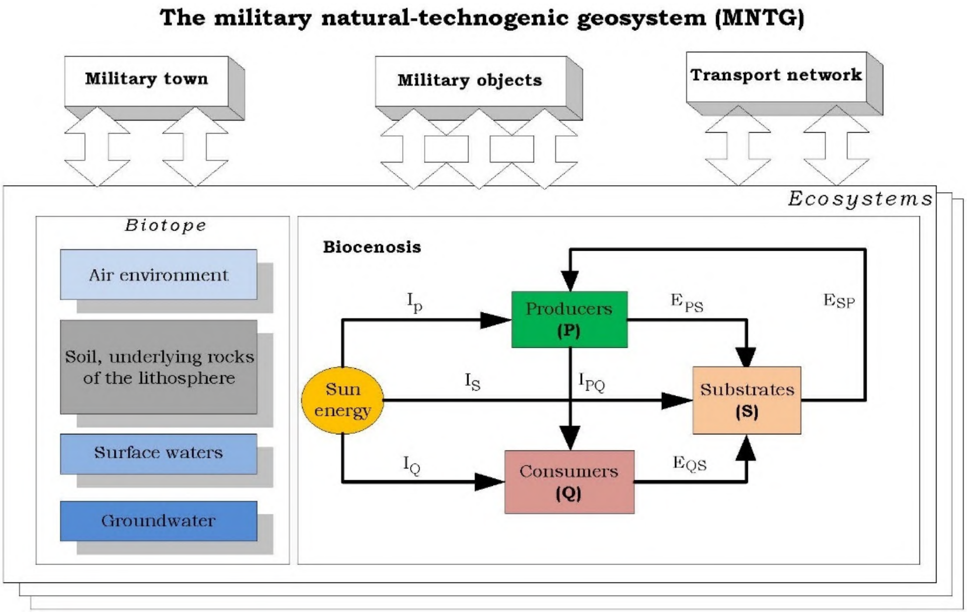

Figure 1. Block diagram of the militarynatural-technogenic geosystem (MNTG).

According to the hierarchical structure of natural geosystems, this scheme identifies the position of MNTG as a subject of study at the landscape and ecosystem levels. By biomass of an ecosystem, means the amount of functioning living matter, expressed in units of mass and related to unit area or volume (it is possible to say that talking about the average density of biomass).

Phyto-mass, zoo-mass, and microorganism mass are distinguished. Producers with biomass $P_i(i = \overline{1,\zeta}), \zeta \in N;\ P^T = (P_1, \ldots, P_\zeta]$ are autotrophic organisms (primarily green plants) capable of creating food from simple inorganic compounds; substrates with biomass S_k $(k = \overline{(1,\xi)}),\ \xi \in N;\ S^T = [S_1, \ldots, S_\xi]$ microorganisms develop; consumers with biomass $Q_j(j = \overline{1,\eta}), \eta \in N; Q^T = (Q_1, \ldots, Q_\eta]$ are heterotrophic organisms (animals (macro-consumers), bacteria and fungi (micro-consumers)) that consume ready-made organic substances but do not break down organic matter into simple mineral components, and feed on producers and other organisms. First-order consumers (those that consume plants) and second, third, etc. order consumers (predators) are distinguished.

The units of measurement of the biomass of the above-mentioned components of ecosystems are:

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- for producers – phytomass: the weight of autotrophic organisms (green plants) per unit area or volume. For example, 200 kg of grass cover per 1 km^2, 80 kg of leaves per 1 tree, and so on.
- for consumers – zoomass: the number of heterotrophic organisms (individuals, bacteria, and fungi) per unit area. For example, 69 individuals of green lizards per 1 km2, 10 common woodpeckers per 5 km^2, and so on.
- for substrates – the weight of organisms per unit area.

The ecosystem model of the polygon will be described by aggregated coordinates P, Q, S (figure 2). To take into account the impact of HS measures and the restorative (rehabilitation) impact of nature conservation measures in the balance relationships adopted in mathematical ecology to describe the functioning of ecosystems [26–28], will add the functions W and U:

$$\begin{cases} \frac{dP_i}{dt} = \left(L_p^i - D_p^i\right) P_i - \sum\limits_{j=1}^{\eta} a_{ij} Q_j + \sum\limits_{k=1}^{\xi} b_{ik} S_k + \Omega_{p_i} + U_{P_i} + W_{P_i}, i = \overline{1, \zeta}, \zeta \in N \\ \frac{dQ_j}{dt} = \left(L_Q^j - D_Q^j\right) Q_j - \sum\limits_{l=1}^{\eta} d_{jl} Q_l + U_{Q_j} + W_{Q_j}, j = \overline{1, \eta}, \eta \in N \\ \frac{dS_k}{dt} = \sum\limits_{j=1}^{\eta} e_{kj} Q_j - \sum\limits_{i=1}^{\zeta} c_{ki} P_i + U_{S_k} + W_{S_k}, k = \overline{1, \xi}, \xi \in N \end{cases} \quad (1)$$

where:

L_P^i, L_Q^j – coefficients of natural growth of producers and consumers, respectively;

D_P^i, D_Q^j – coefficients of mortality of producers and consumers, respectively;

a_{ij} – the rate of biomass consumption of the producer species (i) by the consumer species (j);

b_{ik} – the rate of conversion of biomass of the substrate species (k) to biomass of the producer species (i);

d_{jl} – the rate of consumption of the consumer species (j) by the consumer species (l);

e_{kj} – reproduction of the substrate species (k) by the consumer species (j);

c_{ki} – the rate of consumption of the substrate species (k) by the producer species (i);

Ω_{P_i} – a function characterizing the transformation of solar energy by the i-th producer species (weather and climatic impact);

$W_{P_i}, W_{Q_j}, W_{S_k}$ – a function characterizing the direct harmful impact of HS on the corresponding components of the ecosystem. Modeled by an impulse impact, which abruptly shifts the system to a new position along the corresponding coordinate;

$U_{P_i}, U_{Q_j}, U_{S_k}$ – a function characterizing the direct restorative (rehabilitation) impact of nature conservation measures on the corresponding components of the ecosystem. It consists of the sum of natural (external migration and succession) and artificial restoration measures.

The coefficients L, D, a, b, c, d, e (indices are omitted) are complex functions of the vector of natural-climatic factors of the polygon $\aleph$, the nature, type, intensity of pollution, internal (related to military activities), background, and externally introduced (from technogenic hazardous objects located outside the polygon) pollutants, i.e., components of the generalized pollution vector Z and the rhythm (chronology) and activity of military activities. The rhythm and activity of military activities are determined by the vector of military activity parameters V.

The generalized pollution vector Z consists of concentrations of pollutants (compounds) present in the given territory. The vector of military activity parameters V includes data on the volume, intensity, duration, and periodicity of military activities.

It is particularly important to emphasize that the impact of pollution occurs slowly and manifests itself after a certain time following the accumulation and "assimilation" of these pollutants by the environment.

Thus, the coefficients of equations (equation (1)) (indexes are omitted) are complex functions of $\aleph, Z, V : L = L(K), D = D(K), a = a(K), b = b(K), c = c(K), d = d(K), e = e(K)$, where $K = \{\rho(\aleph), \Lambda(z), \theta(V)\}$ is a tuple of scalar functions. The form of the functions of natural-climatic factors $\rho(\aleph)$ and their parameters are determined by special observations of climate changes in the region. During the time interval of assessment and forecasting of the state of the ground ecosystems of the military training ground ($T \cong 10$ years), it is assumed that the values of the function $\rho(\aleph)$ are equal to the averaged values over a period of approximately $50 \div 100$ years, since the function of climate parameter changes includes periodic fluctuations with periods that exceed several hundred and a thousand years [29]. It should be emphasized that seasonal weather deviations from the mean value are considered as random parametric disturbances, the characteristics of which can be identified based on multi-year observations and taken into account in the corresponding algorithms.

The pollution function $\Lambda(Z)$ is determined algorithmically. The measurement results of the components of the Z vector are recalculated into a generalized pollution index I (see above).

The function of HS parameters $\theta(V)$ controls the structure of the system of equations (1) and logically coordinates the direct influence of W and the action of pollution Z.

Finally, the dependence of the coefficients in equations (1) on the pollution index takes the form $f(t) = f_0 + f_1 \times exp(f_2 \times I_{(t)})$, where f is replaced accordingly by L, D, a, b, c, d, e with their subscripts, and coefficients f_0, f_1, f_2 are subject to current identification.

In assessment tasks, the pollution index I is calculated for the current time t of observation of the pollution vector Z. In problems of assessing the pollution index I, it is calculated at the current observation time t of the pollution vector Z. In the problem of predicting the pollution index I, it is calculated at a future time t based on the knowledge of the function $\theta_{(V)}$, which is given in the form of a military operation plan.

By linearizing equations (1) near the stable equilibrium point of the polygon mesoecosystem (a mesoecosystem unaffected by human activity), obtain a system of equations in the deviations of the biomass of producers, substrates, and consumers:

$$\dot{X}(t) = A(t)X(t) + \Delta\Omega(t) + \Delta W(t) + \Delta U(t)$$

where:

$X(t)^T = (\Delta P_1, \ldots, \Delta P_\zeta; \Delta Q_1, \ldots, \Delta Q_\eta; \Delta S_1, \ldots, \Delta S_\zeta]$;

$A(t)$ – is a square matrix of size $n \times n (n = \zeta + \eta + \xi)$, n – the number of components in the system), whose elements depend on the time-varying level of pollution caused by HS at the landfill (or external landfill pollution);

$$\Delta\Omega^T(t) = [\Delta\Omega_{P_1}(t), \ldots, \Delta\Omega_{P_\zeta}(t); \underbrace{0, \ldots, 0}_{\eta}; \underbrace{0, \ldots, 0}_{\xi}],\ \Delta W^T(t) = \left[\Delta W_{P_1}, \ldots, \Delta W_{P_\zeta}\right];$$

$$\left(\Delta W_{Q_1}, \ldots, \Delta W_{Q_\eta};\ \Delta W_{S_1}, \ldots, \Delta W_{S_\xi}\right\rfloor\ \Delta U^T(t) =$$
$$= \left(\Delta U_{P_1}, \ldots, \Delta U_{P_\zeta};\ \Delta U_{Q_1}, \ldots, \Delta U_{Q_\eta};\ (\Delta U_{S_1}, \ldots, \Delta U_{S_\xi}\right\rfloor$$

– matrices of size $n \times 1$ composed of deviations of the corresponding components $\Omega_{P_i}, W_{P_i}, U_{P_i}, W_{Q_j}, U_{Q_j}, W_{S_k}, U_{S_k}, i = \overline{1,\zeta}; j = \overline{1,\eta}; k = \overline{1,\xi}$.

Therefore, it is proposed to decompose such an ecosystem into a series of subsystems of homogeneous biocenosis and to aggregate the components of the model to the maximum extent possible (minimizing its dimension) by using corresponding summary indicators (indices) regarding the state of producers, consumers, and substrate. System ecologists determine which specific indicators to use for building the aggregated model systems (equation (1)) based on objective observations [30].

Thus, the entire terrestrial ecosystem of military action is divided into subsystems, for each of which an individual aggregated simulation mathematical model is developed.

Mathematical models (MM) of ecological subsystems are aggregated three-dimensional MMs, which differ in that first-type models are linear (stable), and second-type models are nonlinear (logistic).

At the core of the hierarchy of complex geosystems and their diversity lies a clear and implicit division of two main ways of perceiving information about the environment [30]: biology-ecological, where the hierarchical series is structured according to the scheme: of location and community – ecosystem – biome; ecological and geographical: landscape element – landscape – ecoregion. However, this classification cannot be considered unambiguous. For instance, habitats are often interpreted through abiotic characteristics (environment-forming factors) that determine the conditions for the existence of a species in a specific territory of the HS. However, in relation to animals, vegetation is usually considered as a characteristic of the habitat and a criterion for its selection. As a result, the location becomes comparable in volume to the ecosystem of the HS territory.

If consider one of the blocks or elements of the natural environment in MNTG (figure 2), it is in a quasi-stationary state with internal equilibrium. However, at the border of homogeneous media, there are observed mutually exchange flows of mass transfer that can be activated by ingredients of military origin and military-technogenic energy fields.

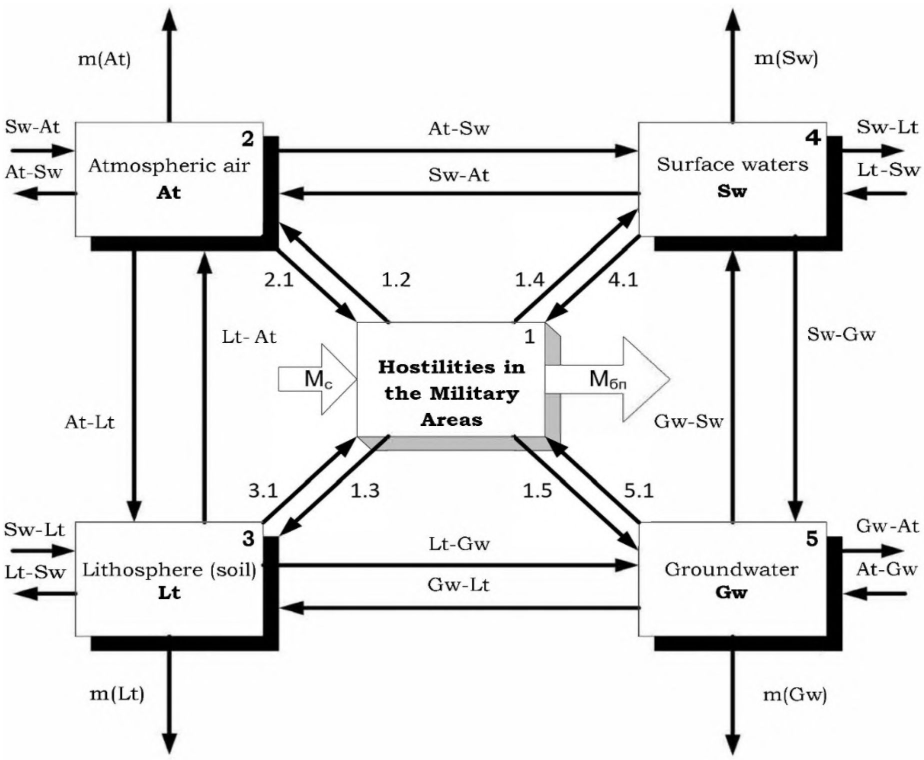

Figure 2. Scheme of interaction of the HS with the components of the environment in the MNTG (for an explanation of the designations, see table 1 [1].

4. Discussion

The general boundaries of MNTG are rather arbitrary, blurred, and determined by the level of natural or altered geochemical background. The flows associated with the "Hostilities in the Military Areas" block are marked with digital indices. The classification of these streams is given in table 1.

The considered scheme of MNTG has a general structural character. In some specific cases, the location of military objects may result in some streams being zero, and the blocks may be transformed or excluded altogether from consideration. The generalized vector index consists of integral pollution indicators according to the corresponding hazard classes $(I_{\Sigma}^{1}, \ I_{\Sigma}^{2}, \ I_{\Sigma}^{3}, \ I_{\Sigma}^{4} \ )$ or integral pollution indicators according to the corresponding components of the abiotic environment of the MNTG $(I_{\Sigma A} \ I_{\Sigma G} \ I_{\Sigma L^p} \ I_{\Sigma L^g})^T$. The impact of pollution occurs sometime after its deposition in the abiotic and biotic components of the MNTG, when the formation of mobile forms in the "soil-plant" system or on the surface of plants begins.

Consider the indicators of MTL, which, by being captured from UAVs and satellite images of remote sensing, make it possible to determine the level of damage to the natural ecosystem's territory caused by HS factors. A classification of the relevant indicators was developed, which

Table 1. Classification of flows between MNTG blocks [1].

Blocks	Combat training	Atmospheric air	Lithosphere	Surface water	Groundwater	Main processes Mass transfer
Hostilities in the MA (1)	–	1.2	–	–	–	Molecular and convective diffusion, filtering, sorption
	–	–	1.3	–	–	
	–	–		1.4		
	–	–	–		1.5	
Atmosphere (2)	2.1	–	–	–	–	For the needs of the HS
	–	–	At-Lt	–	–	Deposition, sorption
	–	–	–	At-Sw	–	Same
	–	–		–	–	Infiltration
Lithosphere (3)	3.1	–	–	–	–	For the needs of the HS
	–	Lt-At	–	–	–	Weathering
	–	–	–	Lt-Sw	–	Leaching
	–	–	–	–	Lt-Gw	Same
Surface water (4)	1.4	–	–	–	–	For the needs of the HS
	–	Sw-At	–	–	–	Evaporation, desorption
	–	–	Sw-Lt	–	–	Sorption, precipitation
	–	–	–	–	Sw-Gw	Filtering
Groundwater (5)	5.1	–	–	–	–	For the needs of the HS
	–	Gw-At	–	–	–	Evaporation, desorption
	–	–	Gw-Lt	–	–	Sorption, precipitation
	–	–	–	Gw-Sw	–	Unloading into erosion bases

is presented in table 2.

Table 2: Characteristics of factors MTL.

Classes of HS territories	Types of disorders in the natural ecosystem	Indicator
	Mechanical impact	
I, II, III	Extraction and replacement of the humus layer with artificial soils during the placement of planar localization fortifications	The ratio of the area of these plots to the area of the disturbed tract
II, III	Drainage ditches	Length, depth, density
I, II, III	Military facilities	Share of paved surface area, height and density of buildings and structures BO
I, II, III	Unpaved roads without hard surface	The width of the carriageway, the prevalence of erosion furrows, thermokarst and other formations
I, II, III	Highways with backup notches	The width of the carriageway, the power of covering the sand and gravel litter, the power and area of the intersection of the recesses
II	Compaction of the upper layers of the soil during the indiscriminate movement of wheeled and tracked military equipment with a change in the species composition of vegetation	Density of traces of the movement of military equipment
II	Channels	Depth, width on the upper eyebrows, water level, flow flow rate
II, III	Deflections	Area, deflection power, groundwater level rise power
II	Pits	Area, depth, water level
II	Dams and dams	Length, height, leakage of leaked moisture, water flow mode
II	Linear communications that impede free movement on the ground	Height, prevalence of erosion
II, III	Shafts formed as a result of the construction of underground utilities	Length, depth, density
III	Soil contamination with metal waste in the form of sleeves and other fragments of shots at the starting positions for firing	Area
III	Contamination of soils in artillery boilers with shrapnel from the explosion of ammunition of various sizes, explosives that did not fully burn, and ammunition that did not explode.	Area, depth.

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Continued from table 2

Classes of HS territories	Types of disorders in the natural ecosystem	Indicator
III	Destruction of soil cover in artillery boilers	Area
III	Trenches and starting positions for shooting	Length, depth, width along the upper eyebrows, volume
III	Formation of the so-called recesses produced in the form of craters from explosions of ammunition	Area, deflection power, groundwater level rise power
III	Formation of bulk landforms as a result of fortification works	Length, height, width along the upper eyebrows
II, III	Formation of so-called “revived” ravines, landslides, soil sedimentation	Depth length, width along the upper eyebrows
II	Waterlogging of terrain on tracks in areas of movement of military wheeled and tracked vehicles	Area
	Chemical exposure	
I, II	Air pollution as a result of the emission of exhaust gases from internal combustion engines	
I, II, III	Air pollution as a result of the emission of exhaust gases from internal combustion engines, powder gases from firing and gaseous substances of explosive conversion of ammunition	Concentration of pollutants in the environment, excess of MPC by certain components of pollutants, volumes of emissions and discharges into the appropriate environment
I, II, III	Contamination of surface and groundwater as a result of pollutants due to sedimentation, filtration and surface runoff	
I, II, III	Soil pollution due to pollutants	
	Physical impact	
II, III	Thermal pollution of the environment due to changes in the thermal balance of the environment from working military equipment, shooting at firing positions, explosions and fires from the ignition of forest and litter	Heat flow power
II, III	Acoustic pollution of the environment from working military equipment as a result of firing and explosions of ammunition	Pressure drop, sound pressure level, sound intensity level, propagation speed and sound frequency
II, III	Vibrational pollution of the environment from working military equipment, shooting at firing positions and explosions	Vibration speed level

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Continued from table 2

Classes of HS territories	Types of disorders in the natural ecosystem	Indicator
II, III	Electromagnetic pollution from radar and radio communications on military equipment	The intensity of electromagnetic field radiation, the intensity of the electromagnetic field, the oscillation frequency of the waves
	Biotic effects	
I, II, III	Complete destruction of forests due to deforestation	Cutting area, productivity of the destroyed phytocenosis
I, II, III	Cutting deforestation with a change in the direction of land use for the military	Length and width of the cuts, the ratio of the cutting area to the area of the disturbed tract
I, II, III	Depletion (destruction) of animal species populations as a result of their fishing	Species, population size
II, III	Displacement of animal species populations as a result of depletion of food supply	Species, population size
II, III	Depletion (destruction) of hydrobiont populations as a result of violation of the thermic and hydrodynamics of water bodies	Species, population size
III	Depletion (destruction) of animal species populations as a result of ammunition damage	Species, population size

Based on the main provisions of the theory of biocenology, a working hypothesis can be put forward that a necessary and sufficient condition for the self-healing of the biota of the ecosystem in operational zones of HS is the preservation of the viability of the edifier sinusia of its phytocenosis [3, 4].

Several full-scale studies have shown that the degradation of ecosystems is almost irreversible when the population density of edifier group of species (the main forest-forming species in forest ecosystems) decreases by two or more times [3, 26]. The disadvantage of using ecosystem productivity as an indicator characterizing the degree of military-anthropogenic damage to the natural environment is its ambiguity due to its change under the artificial action of various factors. Military-technogenic factors usually lead to degradation of ecosystems and a decrease in their productivity. However, some types of anthropogenic influences can destroy the balance of the natural ecosystem by causing a sharp increase in biological productivity (e.g., the process of eutrophication of reservoirs when mineralized or biologically enriched liquid waste is discharged into them). Therefore, it is advisable not to use the absolute value of the change in productivity or its relation to the basic value of the productivity of the primary (background) ecosystem to assess the degree of impact on the ecosystem.

MTL on the environment makes changes in the mechanism of homeostasis due to the deformation or destruction of feedback, which leads to the gradual replacement of primary ecosystems with less productive ones. Since the existence and functioning of any ecosystems are determined by the leading (edifier) role of a rather limited number of species, mainly plants, military-anthropogenic action on edifiers leads to violations and changes in other components of ecosystems [26, 27, 30]. From the outside, this process is expressed in the reduction and rupture of the ranges of edifier species in primary ecosystems and the transfer of the main role in creating the bioenvironment and drawing up the structure of the biocenosis to other species. Conversely, any violations of ecosystems not associated with the death of edifiers do not lead to a noticeable degradation of the ecosystem or its components. With this approach to assessing the state of the ecosystem, a quantitative change in the population density of autochthonous edifier species could become an indicator of the degree of military-anthropogenic damage to the ecosystem, and the time of action could be attributed to the indicator of its speed. Considering the significant analogy between pyrogenic processes and military-anthropogenic action in the structure and nature of the biota violation, it is possible to classify zones of military-anthropogenic destruction in the zone of HS according to the state of edifier sinusia and give a point assessment of the ecosystem's ability to self-heal (table 3).

Table 3. Classification of levels of military-technogenic disturbance of natural ecosystems.

The value of the criterion, violation on a 5-point scale	The degree of ecosystem disruption	The degree of artificial violation	Share of reduction of types of edifiers	Characteristics of the state of the ecosystem and the possibility of self-healing after the removal of the military-technogenic load
I	Background	Too Small	Up to 10 average 5	Rapid self-healing
II	Weak	Small	11−25 average 18	The oppressed state of most species, the ability to self-healing is fully preserved
W	Moderate	Action on the verge of preserving biota	26−50 average 38	Changing the ratio and role of dominant species in the community. The time of self-healing is very long; the possibilities of self-healing are uncertain
IV	Strong	Destructive action	51−80 average 65.5	Changing the qualitative composition of the self-healing community is impossible. The inevitable emergence of new technogeosystems
V	Very strong	Catastrophic effect	80−100 average 90	The complete destruction of the indigenous community and the removal of land from natural circulation for a long time

Under the military-anthropogenic influence (I and II class), effective and constant monitoring of the density of populations of edifier species is necessary, and work on the reclamation of these territories (especially in class III) should be aimed primarily at restoring the edifier sinusia that formed the basis of the ecosystem before the start of the HS.

5. Conclusion

The biologically justified permissible threshold value of technogenic changes in the phytocenosis edificator sinus of the ecosystem is of paramount importance for determining development paths and selecting database management in the face of inevitable military and technological intrusion into the natural equilibrium ecosystem. Experimentally determined indicators should influence the choice of nature conservation and restoration measures in planning databases, but they do not allow for an integrated characterization of the degree of military-technological disturbance of the ecosystem as a whole.

In this article, a mathematical model (equation (1)) has been developed that:

- adequately reflects the impact of combat operations on biocenoses of educational facilities;
- can be used as a mathematical model of phenomena, the parameters of which, with sufficient experimental data, are identified (calibrated) using identification algorithms with the model;
- after identification (calibration), it can be included in algorithms for complex assessment and prediction of the state of terrestrial ecosystems affected by combat operations.

Of the existing indicators in modern mathematical ecology, productivity indicators are the most suitable for this purpose. For natural equilibrium ecosystems, the productivity of the biocenosis correlates well with its complexity and species composition. Therefore, the suppression or destruction of any species as a result of the impact of combat operations inevitably affects the productivity of the biocenosis, and thus, it can serve as a quantitative assessment of the depth of the military-technogenic impact on the ecosystem.

To assess the corresponding level of changes, the system of indicators presented in table 2 can be used, which is interrelated with the levels of military-technogenic violations (table 3).

With sufficient accuracy for engineering assessments, the primary productivity indicator (biomass produced by producers per unit area per unit time during the growing season) can be used. By applying biology-accepted methods and conducting regular observations using remote sensing satellites or unmanned aerial systems to monitor changes in this indicator over time and space, it is possible to determine both the overall dimensions of military-technogenic impact zones and the dynamics and pace of this process when using various weapons systems and military equipment.

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References

[1] Dovgy S O, Ivanchenko V V, Korzhnev M M, Kurilo M M, Trofimchuk O M *et al.* 2016 Assimilation potential of the geological environment of Ukraine and its assessment (Kyiv: Nika-Center)
[2] Mykhailova A, Chumachenko S, Morsch Y and Partalian A 2016 *Naukovij visnik: civil′nij zahist ta požežna bezpeka* 23–33
[3] Dudkin O V, Yena A V and Chumachenko S M 2003 *Assessment and directions of reduction of threats to biodiversity of Ukraine* (Kyiv: Khimdzhest)
[4] Sytnyk Y I, Lysenko O I, Chumachenko S M *et al.* 2006 *Napriamy vdoskonalennia pryrodookhoronnoi diialnosti v Zbroinykh Sylakh Ukrainy [Directions for improving environmental protection activities in the Armed Forces of Ukraine]* (Kyiv: National Scientific Research Center of Defense Technologies and Military Security of Ukraine)
[5] Ma Y, Lyu D, Sun K, Li S, Zhu B, Zhao R, Zheng M and Song K 2022 *Land* **11**(10) 1810 ISSN 2073-445X URL https://doi.org/10.3390/land11101810
[6] Pettersson S, Savage V M and Jacobi M N 2020 *Phys. Rev. E* **102**(6) 062405 URL https://link.aps.org/doi/10.1103/PhysRevE.102.062405

[7] Veerkamp C J, Schipper A M, Hedlund K, Lazarova T, Nordin A and Hanson H I 2021 *Ecosystem Services* **52** 101367 ISSN 2212-0416 URL https://doi.org/10.1016/j.ecoser.2021.101367

[8] Mesquita S, Capelo J, Gama I, Marta-Pedroso C, Reis M and Domingos T 2021 Using Geobotanical Tools to Operationalize Mapping and Assessment of Ecosystem Services (MAES) in Southern Portugal *Tools for Landscape-Scale Geobotany and Conservation* ed Pedrotti F and Box E O (Cham: Springer International Publishing) pp 127–159 ISBN 978-3-030-74950-7 URL https://doi.org/10.1007/978-3-030-74950-7_7

[9] Perennes M, Campagne C S, Müller F, Roche P and Burkhard B 2020 *Land* **9**(10) 348 ISSN 2073-445X URL https://doi.org/10.3390/land9100348

[10] Laporta L, Domingos T and Marta-Pedroso C 2021 *Land Use Policy* **109** 105712 ISSN 0264-8377 URL https://doi.org/10.1016/j.landusepol.2021.105712

[11] Hui D, Biggs R, Scholes R J and Jackson R B 2008 *Biological Conservation* **141**(4) 1091–1094 ISSN 0006-3207 URL https://doi.org/10.1016/j.biocon.2008.02.001

[12] Barbier E B, Acreman M C and Knowler D 1997 *Economic valuation of wetlands: a guide for policy makers and planners* (Gland, Switzerland: Ramsar Convention Bureau) URL https://www.researchgate.net/publication/246010067

[13] Trame A M and Tazik D J 1995 The Implications of Ecosystem Management for Threatened and Endangered Species Conservation by the U.S. Army Tech. Rep. 95/27 USACERL URL https://apps.dtic.mil/sti/citations/ADA302406

[14] Bryhn A, Kraufvelin P, Bergström U, Vretborn M and Bergström L 2020 *Environmental Management* **65**(5) 575–586 ISSN 1432-1009 URL https://doi.org/10.1007/s00267-020-01260-1

[15] Singer S, Wang G, Howard H and Anderson A 2012 *Environmental Management* **50**(2) 329–340 ISSN 1432-1009 URL https://doi.org/10.1007/s00267-012-9873-y

[16] Lady G M and Quirk J P 2007 *Physica A: Statistical Mechanics and its Applications* **381** 351–365 ISSN 0378-4371 URL https://doi.org/10.1016/j.physa.2007.04.001

[17] Hooper D U, Chapin III F S, Ewel J J, Hector A, Inchausti P, Lavorel S, Lawton J H, Lodge D M, Loreau M, Naeem S, Schmid B, Setälä H, Symstad A J, Vandermeer J and Wardle D A 2005 *Ecological Monographs* **75**(1) 3–35 URL https://doi.org/10.1890/04-0922

[18] Pimm S L, Jenkins C N, Abell R, Brooks T M, Gittleman J L, Joppa L N, Raven P H, Roberts C M and Sexton J O 2014 *Science* **344**(6187) 1246752 URL https://doi.org/10.1126/science.1246752

[19] Faber M H, Miraglia S, Qin J and Stewart M G 2020 *Sustainable and Resilient Infrastructure* **5**(1-2) 102–124 URL https://doi.org/10.1080/23789689.2017.1417348

[20] Lawrence M J, Stemberger H L, Zolderdo A J, Struthers D P and Cooke S J 2015 *Environmental Reviews* **23**(4) 443–460 URL https://doi.org/10.1139/er-2015-0039

[21] Mills L S, Soulé M E and Doak D F 1993 *BioScience* **43**(4) 219–224 ISSN 0006-3568 URL https://doi.org/10.2307/1312122

[22] 2008 *Environmental Guidebook for Military Operations* URL https://www.defmin.fi/files/1256/Guidebook_final_printing_version.pdf

[23] 2017 *Military Environmental Protection: Canadian Armed Forces Environmental Aide-Mémoire for Deployed Operations* 3rd ed URL https://publications.gc.ca/collections/collection_2018/mdn-dnd/D2-377-2017-eng.pdf

[24] Gann G D, McDonald T, Walder B, Aronson J, Nelson C R, Jonson J, Hallett J G, Eisenberg C, Guariguata M R, Liu J, Hua F, Echeverría C, Gonzales E, Shaw N, Decleer K and Dixon K W 2019 *Restoration Ecology* **27**(S1) S1–S46 URL https://doi.org/10.1111/rec.13035

[25] Strona G and Bradshaw C J 2022 *Science Advances* **8**(50) eabn4345 URL https://doi.org/10.1126/sciadv.abn4345

[26] May R M 2001 *Stability and Complexity in Model Ecosystems* Princeton Landmarks in Biology (Princeton: Princeton University Press)

[27] Maynard-Smith J 1978 *Models in Ecology* revised ed (Cambridge University Press)

[28] Kachynskyi A B 2004 *Safety, threats and risk: scientific concepts and mathematical methods* (Kyiv: Institute of National Security Problems, National Academy of the Security Service of Ukraine)

[29] Marcott S A, Shakun J D, Clark P U and Mix A C 2013 *Science* **339**(6124) 1198–1201 URL https://doi.org/10.1126/science.1228026

[30] Lysenko O I, Chumachenko S M, Yavisya V S, Guida O G, Novikov V I and Sushyn I O 2022 *Včenì zapiski Tavrìjs′kogo nacìonal′nogo universitetu ìmenì V. Ì. Vernads′kogo* **33(72)**(4) 103–112 URL https://doi.org/10.32838/2663-5941/2022.4/17

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Perspectives of nuclear energy development in Ukraine on the global trends basis

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Abstract. The article examines global trends in the development of the nuclear power industry. It includes the following: extending the operating life of nuclear power units; development of atomic energy in the context of the Paris Agreement; development of nuclear-hydrogen energy; synergistic interaction of renewable energy sources and nuclear power plants; introduction of new reactor technologies. The attitude of different countries of the world to atomic energy is described. It is determined that China and India are the leaders in developing nuclear power. It was determined that small modular reactors are considered transformative reactors that will contribute to the further development of atomic energy in the world. The advantages of small modular reactors in comparison with reactors of large capacity are described, and recommendations for selecting small modular reactors for Ukraine are formulated. Installation of small modular reactors at the operational sites of the NPPs of Ukraine can reduce the financial costs of their construction. Therefore, it will contribute to the sustainable development of the nuclear energy industry of Ukraine.

1. Introduction
The complex problem should be solved to ensure the long-term development of humankind. The issue includes the maintenance of energy and economic and environmental security. Therefore, it is necessary to unite world efforts in the search for innovative directions of technological development that ensure a stable and secure future to solve the outlined problems [1]. Currently, the international energy community emphasizes the global revival of nuclear energy and the rapid

development of renewable energy sources. The situation is evidenced by the active construction of new and modernization of existing nuclear power plants (NPP) in many countries [2].

Further digital transformation of society is essential to ensure the sustainable development of humankind. Such change requires an increase in energy consumption due to the need to process ever-increasing volumes of data. At the same time, growth in energy consumption leads to:

1) depletion of energy sources (problem of energy conservation and diversification of energy production types);
2) climate change (the problem of reducing carbon footprint involves transforming the electricity generation sector against the background of reducing the operational resource of existing energy capacities).

Azarov and Zadunaj [1] indicates various international initiatives in the global field of nuclear energy aimed at developing new projects to combine the efforts of many countries in creating innovative nuclear energy technologies. These initiatives are designed to ensure energy security, reduce atomic materials' distribution risks, and solve the problem of radioactive waste. Also, these ideas became the basis of the international project INPRO operating under the International Atomic Energy Agency (IAEA).

Interest in small modular reactors (SMRs) and their applications is growing worldwide. The main driver for SMR development is to meet the need to produce electricity for a broader range of users and applications, replace aging large-capacity reactors, and improve safety. SMRs include new-generation reactors designed to produce electricity up to 300 MW according to the accepted definition of the IAEA. Their components can be manufactured at the factory and transported as modules to the installation site. SMRs can be deployed as a single or multi-module installation. In addition, many SMRs have increased protection properties and safety functions [3].

Hussein [4] emphasized that SMRs are the next stage in developing nuclear reactors and are transformative by many criteria. SMRs are seen as a way to overcome cost overruns and construction delays where sizeable atomic power reactors were supposed to operate. SMRs can play an essential role in addressing climate change by providing a low-carbon source of electricity. They can also help alleviate the problem of nuclear waste disposal by burning spent fuel and nuclear waste.

Examining government documents regarding the regulation of nuclear energy issues in Ukraine for 2018-2019, we see the following:

1) SE "NAEK "Enerhoatom" and Holtec International signed a Memorandum of Understanding on cooperation in the use of SMR-160 in Ukraine. The Memorandum states that it is planned to license SMR-160 technology in Ukraine further to build these reactors at Ukrainian nuclear power plants and to localize production of SMR-160 equipment at Ukrainian enterprises partially;
2) SE "NAEK "Enerhoatom", State Scientific and Technical Center for Nuclear and Radiation Safety and Holtec International signed an agreement on the creation of an international consortium for "introduction of the small modular reactor (SMR) SMR-160 technology in Ukraine" [2, 5].

Therefore, we state that SMR use is also lobbied at the state level in Ukraine.

It was planned to end the operation period of some power units of the NPP of Ukraine between 2030 and 2040. Such power units already had an extended operation period. The fastest choice of the reactor type technology for the construction of replacement and new NPP power units is relevant [6], taking this into account and taking into account the duration of the creation of a nuclear installation.

Four nuclear power plants in Ukraine (15 power units with water-water power reactors) were operating in Ukraine at the beginning of 2022. Their capacity was 13,835 GW. Zaporizhzhya

NPP (6 power units, the largest nuclear power plant in Ukraine) is still under the control of the invaders in the occupied territory for the end of 2022 due to military operations on the part of Ukraine. The construction of SMR on the territory of Ukraine is still updated by the need for a stable electricity supply for the post-war reconstruction of Ukraine and its economy.

2. Literature review

Azarov and Zadunaj [1] analyzed nuclear energy development in the world and the impact of large-scale accidents at nuclear power plants ("Fukushima-1") on it. The need to improve the security of nuclear power plants is emphasized. Innovative technologies of the III-generation reactors are described. It was noted that atomic energy is the most critical component of the world's energy balance, and there is no severe alert.

Analysis of the materials of international organizations (International Project on Innovative Nuclear Reactors, International Atomic Energy Agency, Nuclear Energy Agency, etc.) [7–9] and scientific literature showed that only a few countries in the world started construction of SMRs by the end of 2022. Various concepts and project licensing are still discussed in other countries.

Nosovskyi [10] determined that there currently needs more technical, economic, and scientific justification for the SMR's operation. SMRs are only being developed worldwide, and their operation benefits still need to be confirmed in practice. Furthermore, the analysis showed that SMR technologies used for electricity production are more expensive than power units with a 500-1000 MW capacity.

The report [11] describes the main problems that should be overcome for the large-scale implementation and achievement of economic competitiveness of SMR. An overview of financial and technical aspects, issues of licensing, and legal regulation are presented. Expanding international cooperation in all directions is essential to create a sustainable global SMR market.

Features of SMR modularity and design are described in [4]. The economic advantages of SMRs and flexibility allow them to be used for various purposes. SMRs are considered a means to reduce greenhouse gas emissions. SMR designs incorporate features that were tested and proven in early reactors. They are also relatively safe for the surrounding population.

Azarova and Zadunaj [1] considered existing plans and programs to develop promising "IV generations" reactor technologies. It is necessary to consider several additional factors: principles development for ensuring the acceptability, efficiency, and economic competitiveness of nuclear energy, stability, nuclear and radiation safety, non-propagation, and physical protection.

Currently, SMR concepts can be conditionally divided into five main groups [11]:

1. *Single-module light-water reactors.* Their design uses the proven technology of light-water reactors (LWR) and appropriate types of fuel to create autonomous units suitable for deployment within the concept of distributed generation or capable of replacing small power units operating on fossil fuels;
2. *Multi-module light-water reactors.* They are based on the LWR technology and can be operated as sources of electricity within the framework of the concept of distributed generation or replace medium-sized power units that provide base load;
3. *Mobile/movable reactors.* They are based on LWR technology and allow easily implemented installation movement from one site to another. This category includes reactors of floating power units;
4. *"IV generations" SMRs.* They are based on modern technologies that differ from those used in LWR;
5. *Micromodular reactors.* Their capacity is at most 10 MW. Such reactors can operate in semi-automatic mode, as a rule. Also, they have characteristics that facilitate easily realized transportation compared to larger SMRs; Micro-modular reactors are designed primarily

for off-grid operation in remote areas where they can be competitive with mainstream electricity sources.

Demianiuk [12] defines the characteristics of SMR and the synergy of SMR with renewable energy sources. Progress of SMR projects in the short term and an overview of leading in technical and economic indicators of SMR are described. Finally, a list of priority measures for implementing SMR in Ukraine is outlined.

Classification of SMR projects depending on the novelty of their technical solutions was proposed by Dybach and Plachkov [13]. In addition, a comparative analysis of SMR (SMR-160 Holtec International project) with NPPs operating in Ukraine was made.

Currently, the most developed type is LWR installations with pressurized water among the existing SMR projects. Steam generators are one of the main elements of them. The preferred design is a functional-flow steam generator with functional body movement in tubes with coiled surfaces [14].

Niearonov et al [6] describes the algorithm for choosing reactor technology type based on a comparative evaluation of existing and promising reactors. Adaptation of the KIND-ET toolkit of the IAEA INPRO project on a multi-criteria comparative assessment of nuclear power plants was carried out for the obtained results ranking. Proposals for reactor technology type choice for constructing NPP power units in Ukraine after 2035 are described. Finally, recommendations for optimal reactor technology choices for creating NPPs in Ukraine for 2050 are defined.

The energy of Ukraine, will be endangered unless the country has time to replace NPP power units with new ones within 2040-2050. At the same time, a significant share of the country's human capital will be lost because nuclear energy is a high-tech industry. It requires specialists with a high level of training in various scientific fields. Therefore, developing and implementing programs to transfer nuclear technological knowledge at the state level is essential. The outlined understanding is a vital resource that will determine Ukraine's political and economic realities shortly. Renewal of Ukraine's nuclear power plants is possible in the following directions: construction of SMR and new "large" NPPs [2].

We analyzed the websites of international organizations dealing with nuclear energy issues and scientific literature during working on this research. Functioning of nuclear fuel cycle facilities are considered in publications [1, 2, 4, 15–18], issue of developing mathematical and software tools for assessing the impact t of energy facilities on the environment is considered in works [19–31]. Specifics implementing of alternative and renewable energy sources are described in publications [32–40]. Advanced training of specialists in nuclear energy is discussed in publications [41–44]. The literature review was performed based on open sources and the websites of international organizations [7–9].

Aim is to consider world trends regarding the development of the nuclear power industry and to substantiate the possibilities of building SMR in Ukraine, given their environmental friendliness and safety.

3. Results

We support the opinion of Kilnytskyi [45] that the principles of sustainable development have determined mainly the evolutionary directions of world energy since the beginning of the 21st century. Bet on energy efficiency, energy security, and low-carbon energy with the active construction of renewable energy sources allowed the industry to enter its development's revolutionary and innovative stage. Everything is changed dynamically on the energy map of the planet: the structure of generating capacities, the configuration of energy systems, and the arrangement of national energy markets.

Investments in nuclear energy were stable and promising for a long time. However, the accident at the Japanese NPP "Fukushima 1" (2011) made the world think about security and question the future of atomic energy. Later, talks about global climate change began, and advanced countries took a course on renewable energy. The question arose: will there be a place for nuclear energy in the new "green" world? NPPs do not emit CO_2 and fully fit the carbon bond neutrality policy. At the same time, atomic power plants leave harmful nuclear waste, and the risk of accidents still makes people distrust even high-tech reactors. Therefore, the USA, Germany, Japan, South Korea, and other world powers gradually reduced investments in this industry; the gas crisis occurred in 2021. So, nuclear energy received a chance for revival and a new future [46].

Currently, 440 nuclear reactors are operating in 32 countries. Another 50 are under construction, mainly in Asia. However, the IAEA does not give precise predictions role of nuclear power plants in electricity production worldwide. It depends on whether it will be possible to build new capacities to replace the stations that will be decommissioned. More than half of the active reactors in the world have been operating for more than 30 years. Today, nuclear energy accounts for 10% of global electricity production. According to the low forecast of the IAEA, this share will decrease to 6% by 2050. According to the high estimates, the percentage of nuclear electricity will increase to 12% [47].

Nuclear energy has two advantages over other sources. First, it can provide heat for production processes and cheap and reliable electricity without releasing greenhouse gases. Secondly, nuclear energy currently avoids emissions of 200 million tons of CO_2 annually (equivalent to removing 400 million cars from all world's roads) [48].

Currently, nuclear energy is in trend again. Let's consider how the views of different countries of the world on nuclear energy were changed. Materials for analysis are taken from open sources of information: scientific publications, websites of international organizations, and analytical and reporting materials. Finally, continents and countries grouped the results of the analysis.

3.1. Europe

The **EU** still needs to make a final decision on the status of nuclear energy. There is an ongoing debate regarding including atomic energy in the "green" taxonomy. Taxonomy is a list of environmentally friendly activities. The European Union needs it to show "useful" companies and encourage investors to finance them. Companies with such markers will attract more loans and be supported by the EU authorities. In 2020 scientists from the European Commission recognized nuclear power plants as a safe, low-carbon energy source. But in 2021, the commission refused to include nuclear power plants in the "green" taxonomy due to the problem with nuclear waste disposal. However, the energy crisis in the EU intensified this debate. At the same time, 12 EU countries called the European Commission to recognize nuclear energy as "green" [46].

More than half of **Poland's** energy depends on coal. So, there is also a search for a stable alternative to reduce carbon emissions.

Germany decided to decommission its nuclear power plants after the Fukushima accident. However, seven reactors remain in operation and provide 12% of Germany's electricity. At the same time, renewable energy is successfully developing in the country [47].

Spain has gradually reduced its share of nuclear energy. Seven reactors remain in operation and supply about 20% of electricity. According to government directives, all reactors should be shut down between 2025 and 2035. It is planned to be replaced by stations with renewable energy sources. However, this may affect the timing of the planned shutdowns [47].

France is the informal leader in nuclear energy production in the world. The country's government is most interested in the approval of atomic energy. France operates 56 nuclear reactors. They provide more than 70% of electricity needs. The country is also the world's largest exporter of nuclear power. It also helps build atomic reactors around the globe. At the same time, 12 reactors coming to an end of service life are planned to be turned off.

Along with this, the construction of a new power unit at the Flamanville NPP is underway.

This will be the country's first EPR – a pressurized water nuclear reactor of the third generation with a capacity of 1,650 MW. Construction was delayed for ten years. Flamanville-3 is expected to be launched in 2023 [47, 48].

Slovakia is the country that is building new nuclear power plants in Europe. Four reactors provide half of the country's electricity, and two more are under construction. The situation with two new reactors at the Mohovets NPP demonstrates the general problem of NPP construction. The 2019 opening was delayed due to pressure from neighboring Austria and safety concerns for the power units, which were initially built to Soviet design and modified using "Western" elements [47].

Great Britain ranks tenth in the world for nuclear energy production. "Electricite de France SA (EDF)" began constructing the Hinkley Point C plant in Somerset in 2016. It is expected to be operational in the middle of this decade. Hinkley Point C is expected to supply around 7% of the UK's electricity once connected to the grid. In addition, it is currently underway for the 3,200 MW Sizewell C power station in eastern England. EDF plans to build it in partnership with China General Nuclear Power Group [48].

3.2. North America

Ninety-five reactors are actively operating in the USA, providing 30% of the world's nuclear electricity and remaining its largest producer. NPPs generate about 20% of electricity for the country's needs. From 1978 to 2013, new NPPs were not built. Only in 2012 were permits issued for constructing two new reactors at the Vogtle NPP in Georgia. It happened for the first time in 30 years. New projects began to appear in 2016 when the second power unit of the Watts Bar NPP in Tennessee opened. However, significant delays and rising construction costs led to the closure of two reactors at the V.C. Summer station in 2017 in South Carolina [47]. The development of nuclear power plants in the United States is part of the fight against climate change. The government allocated $1.85 billion to support the nuclear power industry in 2022. This value is 23% more than in 2021. Another $6 billion will be used to extend the service life of the NPP; 2.5 billion will be spent on the construction of experimental reactors [46]. President Biden spoke in favor of nuclear energy and emphasized the expansion of jobs and opportunities that will be created through the development of innovation and investment in the latest small modular reactors [48].

3.3. Asia and the Middle East

China plans to significantly increase the share of nuclear generation in the energy system from 3% to 7.7% in 2035. The country has 49 reactors, and 16 more are under construction. Preference is given to nuclear energy in the country due to excessive air pollution by coal-fired power plants. China is developing and planning to introduce new reactors and increase the number of plants and their capacity. For example, the first SMR may start operating on Hainan Island as early as 2025 [47]. China is ready to build many nuclear power plants on its territory and 30 reactors abroad, competing in this market with France and the USA [46]. In 2021 the President of China was directly present at the foundation laying ceremony of four new nuclear power units in the PRC. Power units 7 and 8 of the Tianwang NPP and 3 and 4 of the Xudapu station will be built using domestic equipment [48].

South Korea announced plans to withdraw from nuclear energy by 2040. As a result, the life of atomic power plants will remain the same, and new facilities will not be built [48].

Japan sees nuclear power as the key to achieving decarbonization goals and reducing greenhouse gas emissions. Therefore, Japan is also considering using nuclear energy by introducing small modular reactors. This is outlined in the country's Green Growth Strategy [48].

The **Indian** government plans to launch nine reactors in three years. The construction of another 12 was approved in 2020. This is the first time a nuclear power plant has been built in the country on such a scale [46]. It is planned to increase the number of nuclear power plants in India within the framework of large-scale infrastructure development programs. Currently, 23 reactors are operating in the country. In addition, 21 new reactors with a total capacity of 15 GW may be installed [48] up to 2031.

The **United Arab Emirates** launched the first Baraka NPP in 2020. It is planned that all four power units of the station, with a total capacity of 5.6 GW, will work already in 2023 and will provide up to 25% of the country's electricity needs [48].

Turkey is building its first Akkuyu nuclear power plant. One of the reasons is a desire to reduce energy dependence. The country imports about 75% of its electricity. The station will have four power units with a total capacity of 4.8 GW. Its first reactor is planned to be launched in 2023 [48].

So, we conclude that China and India became leaders in developing the nuclear energy industry based on the analysis above. Based on the analysis of scientific literature [14, 45, 47, 48], the main problems of the development of nuclear energy in the world are outlined:

- decrease in the competitiveness of nuclear energy and premature shutdown of power units;
- exceeding terms and cost of construction of new NPPs;
- aging of operating power units and need for decommissioning;
- the negative attitude of society against the background of Fukushima and other nuclear accidents;
- the difference in licensing of nuclear reactor projects;
- the need to solve the problem of spent nuclear fuel and radioactive waste;
- the inability of energy markets to attract long-term investments.

We agree with the Lutska [47] that today's security issue remains the most crucial reason for refusing to build new nuclear power plants. It got tougher every time after the accidents at the Chornobyl and Fukushima stations. In 2011 anti-nuclear protests intensified significantly in Europe, where plants are often located near borders with neighboring countries. The next problem is the complex process of nuclear power plant construction. It is often delayed and stopped causing the cost of power units to rise. Also, the issue of handling atomic waste remains relevant. At the same time, some countries see nuclear energy as an opportunity to diversify energy sources, reduce dependence on other energy sources and replace coal-fired power plants [47].

An outline of the world trends in the development of nuclear energy is essential. The research was prepared based on the analysis of various sources [4, 14, 16, 45, 47–50]:

- an extension of the operating periods of nuclear power units;
- development of nuclear energy in the context of the Paris Agreement;
- development of nuclear-hydrogen energy;
- synergistic interaction of renewable energy sources and nuclear power plants;
- introduction of new reactor technologies.

Let's briefly describe the trends outlined above. The critical disadvantage of nuclear energy today is the high capital costs for constructing large atomic power units. Therefore, many countries with operating nuclear power plants are forced to extend the operating periods of their power units. The leading technologies that will ensure the fulfillment of the goals of the Paris Agreement include those with low levels of greenhouse gas emissions. Hydropower, wind, and nuclear power will play an important role. They produce the least amount of greenhouse gas emissions. Every year amount of hydrogen consumption increases. So, the development of hydrogen energy is taking place. Many countries developed their own "Hydrogen Strategy". The world public and scientists predict a significant effect from the operation of hybrid energy systems for the synergistic interaction of renewable energy sources and nuclear power plants. Such hybrid systems will make it possible to generate electricity and provide low-carbon thermal energy for the industry at a price lower than a traditional thermal generation (figure 1).

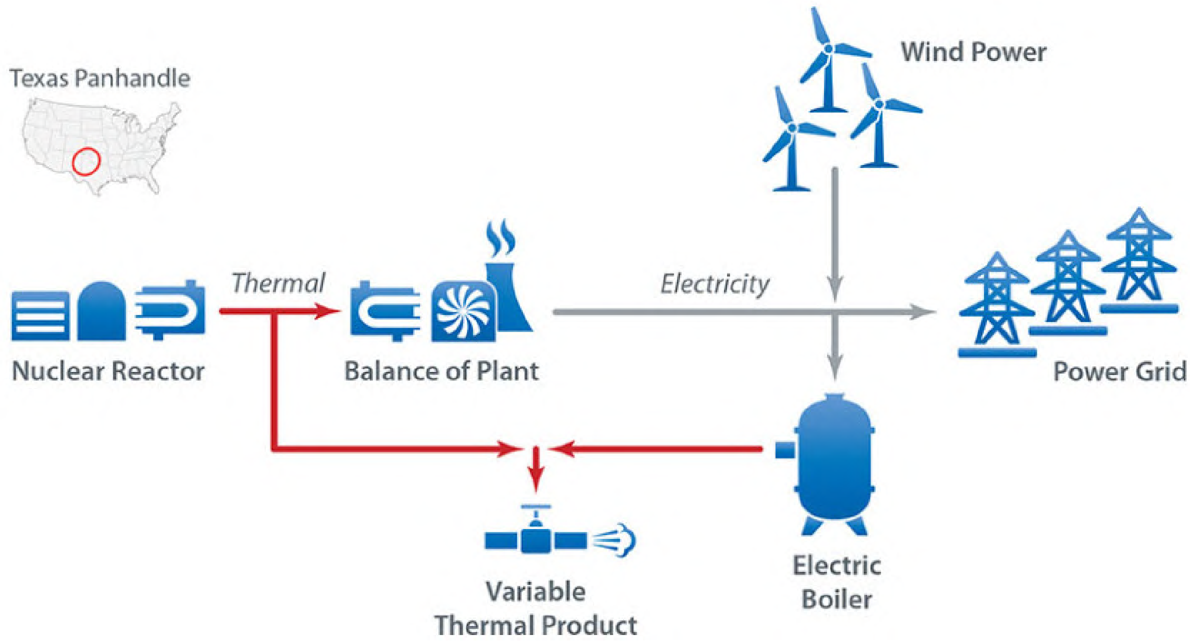

Figure 1. An example nuclear-renewable hybrid energy system configuration [51].

Let's analyze the trend regarding the "introduction of the new reactor technologies" in more detached new reactor technologies caused by the following factors: risk of accident at the nuclear power plant and difficulty of disposal of radioactive waste. The publication [46] indicated that the factors listed above could be leveled by using new reactor technologies. One of the progressive ideas is thorium reactors. Uranium-233 is used for the operation of these systems. The substance is obtained through the irradiation of thorium-232. These reactors are predicted to leave behind less toxic waste. At the same time, there are more thorium reserves in nature than uranium, which is safer to produce. Currently, China decided to build an experimental thorium reactor that will work on an alloy of salts. The reactor will be filled with an alloy of salts. So, it will have a much lower risk of melting or exploding, making the leakage of radioactive components almost impossible. However, thorium is associated with the risk of nuclear propagation. It is hotly debated.

The TerraPower company plans to launch an experimental nuclear reactor in the remote town of Kemmerer (USA). The reactor will be cooled by liquid sodium. There will be no increased pressure in the reactor, So it minimizes the possibility of an explosion. The system will not require external energy sources for cooling. The creators of TerraPower promise to solve the problem of nuclear waste. Now they are stored in concrete containers. Spent fuel from TerraPower will take up two-thirds less space than waste from conventional reactors. Also, the construction of such an object costs much less than usual due to greater use efficiency. This reactor is small in size. It, in turn, reduces capital costs. It produces three times less energy than the average reactor, so it is more profitable to build it [46].

Today, companies and startups worldwide develop new models of nuclear power plants. They should be simpler and cheaper to build, safer, use less fuel, and operate more flexibly. They may influence global trends in the development of atomic energy [47] if the new reactors meet all these criteria.

NPPs with high-power reactors are designed to operate in the base mode. Therefore, it limits the possibilities of using nuclear potential due to the need for daily regulation of loads in the power grid. This drawback can be avoided by switching to SMRs (figure 2). SMRs are cheaper to operate, can be used in shift mode, do not require the construction of powerful underwater power lines, and have higher levels of safety [45].

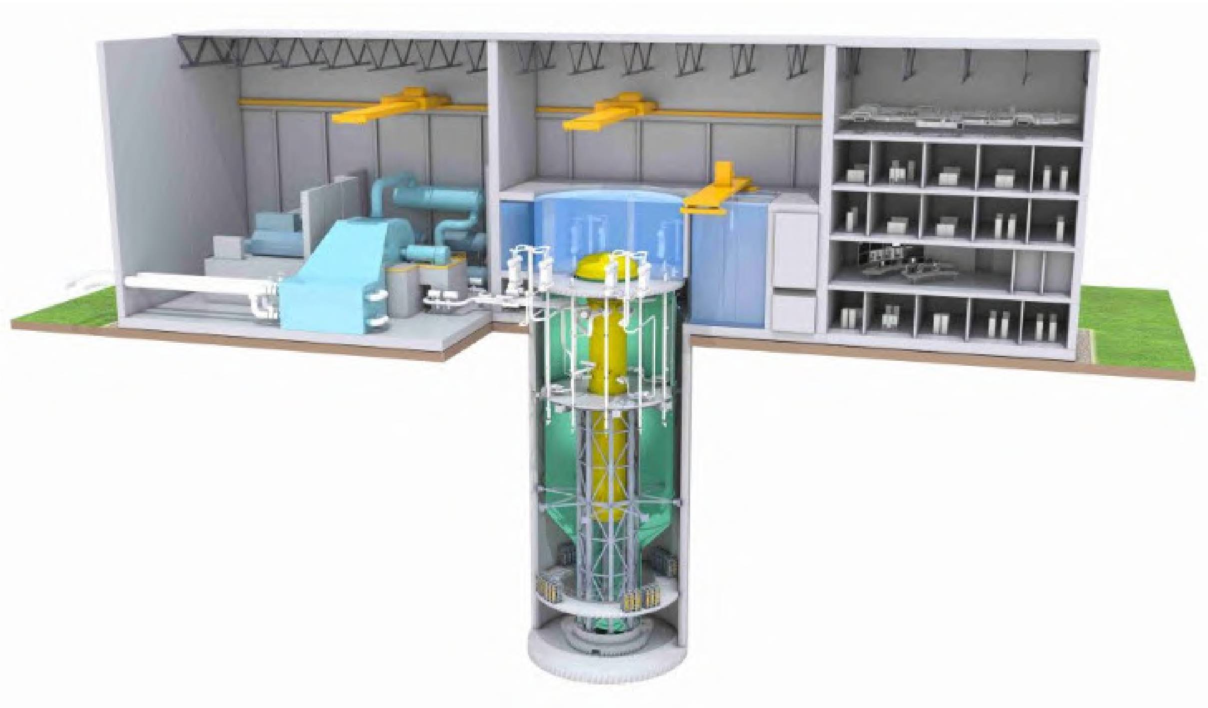

Figure 2. Example of BWRX-300 Small Modular Reactor [52].

Miroshnychenko [46] indicated that SMRs will produce three to four times less energy than conventional ones and will be affordable for underdeveloped countries. In addition, their low cost will make it possible to replace large nuclear power plant reactors that with ending their service life [45].

Dybach and Plachkov described several potential advantages of SMR [13]:

1) higher protection of SMR from undue external influences of natural and artificial nature (possibility of underground placement of the reactor installation). Figure 3 shows this placement of Canada's first SMR;
2) high level of internal self-protection and wide use of passive systems. It allows reviewing (reducing) a set of technological systems necessary for safety, operating in standby mode;
3) modular principle ensures serial production, the possibility of complete factory production of the module and its delivery to the NPP site;
4) operation in power tracking mode (power shift) allows combining SMR with other renewable energy sources.

Figure 3. Example of underground placement of SMR [53].

SMRs can find applications in many areas of nuclear energy use. The steady development of SMRs was revealed as a result of the analysis of the current trends in the development of atomic energy. Currently, the most developed type is LWR installations with pressurized water among the existing SMR projects. Steam generators are one of the main elements of them. The preferred design is a functional-flow steam generator with functional body movement in tubes with coiled surfaces [14].

OECD [11] indicated that worldwide policy-making bodies, enterprises of the nuclear sector, and energy analysts show growing interest in the potential of SMR as a competitive element of low-carbon technologies used in integrated energy systems of the future. In addition, SMRs embody hopes for inherent safety, simplification, and standardization properties. All of this can significantly facilitate and make nuclear power more cost-effective.

SMRs can be placed directly in energy consumption centers. It eliminates the need for external power lines and maintenance in difficult climatic and terrain conditions. Significant reduction in network infrastructure costs allows for increased efficiency and competitiveness of SMR technologies [54].

Gaspar [55] emphasizes that SMRs are smaller and use innovative technologies with many built-in safety features. An important element of their design is minimizing accidents and radioactive emissions. A similar opinion was expressed by Zhou [14]: “SMR possess better safety characteristics and lower amount of radioactive materials (less potential for radioactive release); it is expected that iodine prophylaxis, shelter, evacuation will not be needed to protect public from the SMR".

Considering SMR according to various criteria characterizing their advantages, we will describe the "safety" criteria and its indicators based on [11]:

- reducing the level the severity of emergency modes (a combination of increased levels of simplification and structural integrity is expressed in a smaller number of emergency modes);
- efficiency of passive safety systems (need for active systems decreases, which in the long run simplifies safety assessment, reduces the number of emergency modes, and improves the reactor cooling mode using natural circulation. All this contributes to increasing the time provided for emergency response);
- reduced protective zone outside the site (less need for shielding means and a smaller area of the zone for planning protective measures).

Table 1, table 2 and table 3 compares SMR and high-power reactors according to the criteria "Operational safety," "Infrastructure," and "Personnel resources." This tables was compiled based on publications [6, 12, 54, 55] and open sources.

Ukraine promised to abandon coal burning by 2035. Consequently, the number of thermal power plants will decrease over the years, and domestic energy will gradually lose 30% of its capacity. The decline of thermal power plants will stimulate the development of nuclear power plants and renewable energy facilities. The problem is that 13 out of 15 reactors will become unusable by 2040. Therefore, fourteen power units should be built in the coming decades for the energy transition and replacement of old reactors. Three should be located at the Khmelnytskyi

Table 1. Comparison of SMR and high-power reactors ("Operational safety" criterion).

Indicators	SMR	High-power reactors
Physical safety	Possibility of hidden placement underground, underwater on the territory of military bases, etc. There needs to be more infrastructure, personnel, and length of heating lines.	Risks associated with the extensive infrastructure and territory of the station.
Energy security, infrastructure risks	Integration into the local power system. Flexibility to build up generating capacity. Low distance to the consumers.	Extensive network and consumer life support system risks.
Nuclear and radiation safety	Reduction of the risks and magnitude of caused damage. Absence of "serious accident" consequences.	Probabilistic methods estimate them.
Energy stability	There are no power unit stops due to common causes.	However, the power unit stop occurred due to familiar grounds.
Human factor	We make technical decisions on modularity, quality, and reliability – a minimum number of personnel, a personnel training system, and a department management structure.	The high number of personnel at all stages of the object's life cycle and workshop management structure.

Table 2. Comparison of SMR and high-power reactors ("Infrastructure" criterion).

Indicators	SMR	High-power reactors
Reliable energy supply	Organization of ensuring effective navigation of transit and sea routes, military facilities, etc.	Limited. It is possible with a developed structure of energy networks.
Technical competencies and infrastructure development	Development of competencies within the territory's economy. An educational center, scientific and technological complex, prospective studies of habitats. I am stopping the outflow and employment of the population, particularly the youth.	We were limited by the technology of the power unit (electricity production).
The wide contour of energy conversion and tariff stability	Electricity, heat, fresh water, steam, and hydrogen are modules for the region's infrastructure needs and a reliable life support system.	Limited to electricity production only.
Creation and provision of reliable hybrid energy systems	Ensuring stability, reliability, and quality of the energy carrier, design of hybrid energy systems in local areas, a wide range of capacity changes, and creation and development of industrial nuclear-hydrogen energy.	
Insurance	It is possible for various infrastructure objects.	Not available in its entirety.

NPP, one at the Zaporizhzhya, Rivne, and South Ukrainian NPPs, and eight at new stations. SE "NAEK "Enerhoatom" signed a memorandum with the American company Westinghouse which will participate in constructing five power units worth about 25 billion dollars. Cooperation with Westinghouse SE "NAEK "Enerhoatom" is positive. It is believed that Ukrainian specialists have enough experience to build power units [46].

The first energy cooperatives appeared in Ukraine: several community members united to provide themselves with energy resources. This practice is widespread worldwide, especially in the USA and Germany. In these countries, the total number is calculated in hundreds and thousands, and they unite millions of people. For example, in Germany, 47% of solar energy is produced by citizens and cooperatives. Energy cooperatives are common in Great Britain, Australia, the Netherlands, and Denmark. A Cooperative is also cheaper to administer than a joint-stock company or an investment fund. The primary meaning of energy cooperative for citizens is not to expect mercy from the state or industry monopolies in solving energy supply problems but to develop their energy businesses and earn money independently [45].

The country's energy security and the possibility of further digital transformation of the economy will be endangered if Ukraine does not have time to replace the existing NPP units with new ones during 2040-2050. Also, a significant share of the country's human capital will be lost. Nuclear energy is a high-tech industry and requires specialists with a high level of training in various scientific fields. The "nuclear energy knowledge of Ukrainian specialists" can be classified as a national strategic resource. Therefore, at the state level, it is necessary to develop and implement programs to preserve and transfer nuclear technological knowledge as a resource that will determine Ukraine's political and economic realities shortly [2].

Activities on analyzing prospects for the introduction of SMR technology in Ukraine were also

Table 3. Comparison of SMR and high-power reactors ("Personnel resource" criterion).

Indicators	SMR	High-power reactors
An alternative approach to reloading nuclear fuel	The zone is active for 10-15 years. Filling together with a radioactive installation at notable enterprises. Absence of dose loads on personnel.	Reload every two years. Availability of spent nuclear fuel and radioactive waste infrastructure. Radioactive waste removal. Dose load.
Risks at the decommissioning stage	Large modular dismantling. Reducing the likelihood of exposure to personnel at risk.	Large modular disassembling. They are reducing exposure probability to personnel.
Environmental safety	Local energy system transformation into an ecologically clean system. Significant reduction of emissions (liquid, solid, gaseous) and oxygen combustion. Reduction of environmental consequences.	Placement and assignment restrictions.
Application of waste-free technologies	Development of unavailable resources. Deep processing of minerals, water desalination, waste disposal, etc.	Limitation by purpose.
Social acceptance.	Possibility of visual proof of increased security.	Psychological barriers (after the Chornobyl and Fukushima accidents).

started: working cooperation with potential SMR suppliers (NuScale Power) was established, and work on studying the technical and economic aspects of these reactors is ongoing. In addition, SE "NAEK "Enerhoatom" and "Holtec International" signed a "Memorandum of Understanding" on cooperation in the use of SMR-160 in Ukraine (figure 4).

The work of Demianiuk [12] contains a generalization of SMR safety indicators: frequency of damage to the active zone, the frequency of early/significant release, and the size of the emergency planning zone. In addition, a combination of SMR and renewable energy sources is considered.

Niearonov et al [6] emphasized that using SMR in Ukraine is the most promising direction for developing nuclear energy in Ukraine. At the same time, it is necessary to conduct additional research on determining the optimal ratio of SMR and PWR reactor technologies, considering prospects for deploying renewable energy sources. Priority measures for SMR implementation in Ukraine are described [12]:

1) in-depth strategic analysis of the United Energy System of Ukraine according to international methods (IAEA, OECD);
2) detailing needs of the United Energy System of Ukraine in balancing (maneuvering) capacities and developing technical requirements for SMR;
3) execution of preliminary technical and economic substantiation of SMR construction;
4) development of optimal financial models for the implementation of SMR projects in Ukraine based on public and private partnership.

It is essential to take into account the following aspects [6] during the comparative evaluation of reactor technologies:

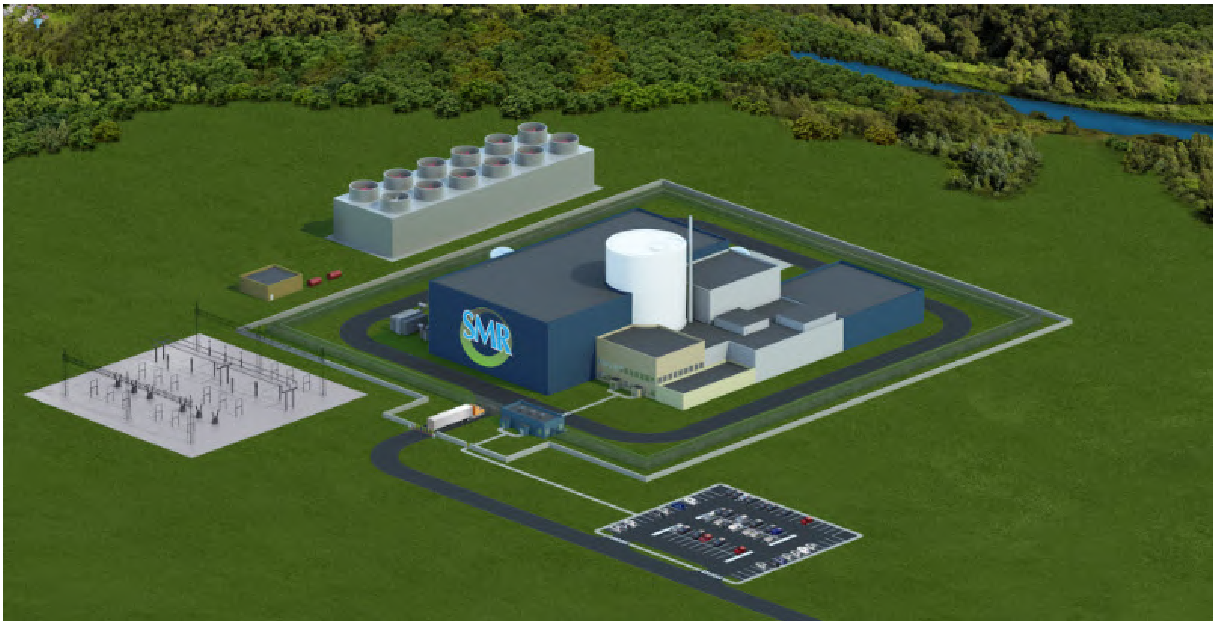

Figure 4. Holtec SMR-160, a 160 MW Electric Nuclear Power Plant [56].

- compliance of reactor technology with international safety standards, criteria of IAEA, WENRA3, EUR4, and comparability with requirements of regulatory documentation of Ukraine on nuclear and radiation safety;
- economy, reliability, the possibility of NPP power units operating in different modes;
- involvement of NPP power units in ensuring conditions of reliable functioning of the unified energy system of Ukraine;
- the possibility of reliable provision of nuclear fuel taking into account own uranium reserves, diversification of suppliers and manufacturers;
- ensuring a non-propagation regime by the legislation and international obligations of Ukraine;
- the possibility of serial construction, further operational support of power units, and production localization of their systems and components.

We agree with the opinion of Vyshnevskyi and Mykytenko [2] that it is impossible to give absolute priority to SMR construction to meet the needs and conditions of functioning of the nuclear energy industry of Ukraine. It is essential to stimulate the entrepreneurial initiative of businesses with the necessary technology and capital. The state's role should remain leading and adequately respond to the existing risks related to the main aspects of private nuclear energy: safe operation of nuclear facilities, countering propagation of atomic weapons, and disposal of nuclear waste.

4. Author contributions

The research results provided in the publication are presented in the aggregate of the joint contribution of individual authors:

- **Oleksandr O. Popov**:
  - Idea and preparation of the draft article.
  - Organization of the authoring team's work and task assignment for article preparation.

- Analysis and synthesis of global trends in nuclear energy development.
- Description of the advantages of small modular reactors (SMR) compared to large reactors.
- Justification of the possibilities of small modular reactors construction in Ukraine considering their environmental friendliness and safety.
- Formulation of article conclusions.

• **Anna V. Iatsyshyn**:
  - Justification of the research relevance and article project preparation.
  - Analysis of scientific publications and websites of international organizations dealing with nuclear energy issues.
  - Analysis of literature sources on the training and qualification improvement of specialists in the energy sector.
  - Identification of important aspects regarding the specialized training of personnel for SMR operation and maintenance.
  - Substantiation of the possibilities of small modular reactors construction in Ukraine considering their environmental friendliness and safety.
  - Formulation of article conclusions.

• **Maryna A. Deineha**:
  - Analysis of literature sources on the operation of nuclear fuel cycle facilities.
  - Examination of how different countries' views on atomic energy have evolved, the results of the analysis are grouped by continents and countries (Poland, Germany, Spain, France, Slovakia, Great Britain, China, South Korea, Japan, Indian, United Arab Emirates, Turkey).

• **Tamara S. Novak**:
  - Analyzed state documents on the regulation of nuclear energy issues in Ukraine.
  - Reviewed how the views of different countries on nuclear energy have evolved. The results of the analysis are grouped by continents and countries.
  - Conducted a comparison of SMRs and large-scale reactors based on the criteria of "operational safety," "infrastructure," and "human resources" using scientific publications and open sources.

• **Dmytro V. Taraduda**:
  - Analyzed materials from international organizations (International Project on Innovative Nuclear Reactors, International Atomic Energy Agency, Nuclear Energy Agency, etc.).
  - Conducted a comparison between SMRs and large-scale reactors based on the criteria of "operational safety," "infrastructure," and "human resources" using scientific publications and open sources.

5. Conclusions

We analyzed scientific publications and websites of international organizations dealing with nuclear energy issues and concluded that nuclear energy is again in trend. Also, the attitude of governments of different countries of the world to atomic energy was considered. It was determined that China and India are the leaders in developing nuclear power.

Global trends regarding the development of the nuclear power industry were considered as a result of the research. They include an extension of the operating life of nuclear power units; the development of atomic energy in the context of the Paris Agreement; the development of nuclear-hydrogen energy; synergistic interaction of renewable energy sources and nuclear power plants; introduction of new reactor technologies.

SMRs are considered transformative reactors that will contribute to the further development of nuclear energy globally. The advantages of SMR compared to high-power reactors include lower time and financial costs for construction and implementation; significant potential for maneuvering energy capacities; higher safety indicators for the environment and personnel; quick response to the needs of the energy market; synergy with renewable energy sources and increasing their efficiency within the framework of a hybrid energy system, etc.

At the same time, SMRs are still under discussion regarding the feasibility of such construction. Only a few countries started their construction. Another vital aspect is the special training of personnel to manage and maintain the SMR.

Military operations on the territory of Ukraine since the beginning of 2022 have confirmed the importance and expediency of the construction of SMR to ensure the energy needs of the state and opportunities for post-war reconstruction and restoration of various sectors of the economy. At the same time, Ukraine's tragic experience with the accident at the Chornobyl NPP requires ensuring environmental safety [57]. Therefore, it uses safe, energy- and resource-saving, low- and zero-waste technologies. Also, preference should be given to light-water (evolutionary) SMR projects. Their technical solutions use the accumulated experience of operation and safety analysis of operational NPPs with VVER. Furthermore, SMRs that can already be installed at the active sites of the NPPs of Ukraine should be chosen. Such actions will contribute to the reduction of financial costs for the construction of SMR and contribute to the sustainable development of the nuclear energy industry of Ukraine.

Therefore, the construction of SMR on the territory of Ukraine will make it possible to reach a new level of development of nuclear energy, ensure a faster transition to the digital economy, and contribute to occupying a key position among countries in the modern atomic energy world space.

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References

[1] Azarov S and Zadunaj O 2020 *Magyar Tudományos Journal* **41** 31–38 URL https://cyberleninka.ru/article/n/innovatsiyni-reaktorni-tehnologiyi-4-go-pokolinnya-i-suchasniy-stan-yih-rozvitku
[2] Vyshnevskyi O and Mykytenko T 2021 *Efektyvna ekonomika* (12) URL https://doi.org/10.32702/2307-2105-2021.12.15
[3] 2020 *Advances in small modular reactor technology developments. A Supplement to: IAEA Advanced Reactors Information System (ARIS)* 2020th ed (Vienna: International Atomic Energy Agency) URL https://aris.iaea.org/Publications/SMR_Book_2020.pdf
[4] Hussein E M A 2020 *Physics Open* **5** 100038 ISSN 2666-0326 URL https://doi.org/10.1016/j.physo.2020.100038
[5] Uatom 2019 Energoatom, SSTC NRS and Holtec International Signed International Consortium Agreement URL https://www.uatom.org/en/2019/06/11/energoatom-sstc-nrs-and-holtec-international-signed-international-consortium-agreement.html
[6] Niearonov Y M, Baybuzenko T Y, Shenderovych V Y, Vlasenko M I, Godun O V, Kyrianchuk V M, Semenov G R and Gromok L I 2020 *Nuclear Power and the Environment* **18** 10–22 URL https://doi.org/10.31717/2311-8253.20.3.2
[7] International Atomic Energy Agency 2023 Atoms for Peace and Development URL https://www.iaea.org
[8] International Atomic Energy Agency 2022 International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) URL https://www.iaea.org/services/key-programmes/international-project-on-innovative-nuclear-reactors-and-fuel-cycles-inpro

[9] Nuclear Energy Agency (NEA) 2020 Home URL https://www.oecd-nea.org
[10] Nosovskyi A V 2020 *Nuclear Power and the Environment* **18** 5–9 URL https://doi.org/10.31717/2311-8253.20.3.1
[11] Organization for Economic Co-operation and Development 2021 *Small Modular Reactors: Challenges and Opportunities* Nuclear Technology Development and Economics (Boulogne-Billancourt, France: Nuclear Energy Agency, Organization for Economic Co-operation and Development) URL https://www.oecd-nea.org/upload/docs/application/pdf/2021-03/7560_smr_report.pdf
[12] Demianiuk V V 2020 *Nuclear Power and the Environment* **18** 23–33 URL https://doi.org/10.31717/2311-8253.20.3.3
[13] Dybach O and Plachkov H 2019 *Nuclear and Radiation Safety* (1(81)) 3–9 URL https://doi.org/10.32918/nrs.2019.1(81).01
[14] Zhou X 2021 *Improvement of the methodology for calculating a once-through steam generator for low-power NPP* Thesis for the degree of Doctor of Philosophy (PhD) in Specialty 143 - Nuclear Energy Odessa Polytechnic State University Odessa URL https://op.edu.ua/sites/default/files/publicFiles/dissphd/dysertaciya_chzhou_143.pdf
[15] Pioro I 2021 Current status of nuclear power in the world URL https://youtu.be/lT1m1QgjCqk
[16] Ramana M V 2021 *IEEE Access* **9** 42090–42099 URL https://doi.org/10.1109/access.2021.3064948
[17] Kyrylenko O V, Basok B I, Baseyev Y T and Blinov I V 2020 *Tekhnichna Elektrodynamika* (3) 52–61 URL https://doi.org/10.15407/techned2020.03.052
[18] Kyrylenko O V, Blinov I V and Tankevych S E 2012 *Tekhnichna Elektrodynamika* (3) 47–48 URL https://previous.techned.org.ua/2012_3/st21.pdf
[19] Zabulonov Y, Popov O, Burtniak V, Iatsyshyn A, Kovach V and Iatsyshyn A 2021 Innovative Developments to Solve Major Aspects of Environmental and Radiation Safety of Ukraine *Systems, Decision and Control in Energy II* ed Zaporozhets A and Artemchuk V (Cham: Springer International Publishing) pp 273–292 URL https://doi.org/10.1007/978-3-030-69189-9_16
[20] Mokhor V, Gonchar S and Dybach O 2019 *Nuclear and Radiation Safety* **2** 4–8 URL https://doi.org.10.32918/nrs.2019.2(82).01
[21] Komarov M, Honchar S and Dimitriieva D 2021 *Nuclear and Radiation Safety* **1** 59–66 URL https://doi.org/10.32918/nrs.2021.1(89).07
[22] Zaporozhets A 2020 Overview of Quadrocopters for Energy and Ecological Monitoring *Systems, Decision and Control in Energy I* ed Babak V, Isaienko V and Zaporozhets A (Cham: Springer International Publishing) pp 15–36 URL https://doi.org/10.1007/978-3-030-48583-2_2
[23] Myrontsov M L 2011 Hardware-methodical laterolog complex for flat well *Geoinformatics 2011 - 10th International Conference on Geoinformatics: Theoretical and Applied Aspects, Extended Abstracts* (European Association of Geoscientists & Engineers) pp cp–240–00023 ISSN 2214-4609 URL https://doi.org/10.3997/2214-4609.20145058
[24] Iatsyshyn A, Artemchuk V, Zaporozhets A, Popov O and Kovach V 2020 Mathematical Approaches for Determining the Level of Impact of Ash-Slag Dumps of Energy Facilities on the Environment *Systems, Decision and Control in Energy I* ed Babak V, Isaienko V and Zaporozhets A (Cham: Springer International Publishing) pp 1–13 URL https://doi.org/10.1007/978-3-030-48583-2_1
[25] Popov O, Iatsyshyn A, Sokolov D, Dement M, Neklonskyi I and Yelizarov A 2021 Application of Virtual and Augmented Reality at Nuclear Power Plants *Systems, Decision and Control in Energy II* ed Zaporozhets A and Artemchuk V (Cham: Springer International Publishing) pp 243–260 URL https://doi.org/10.1007/978-3-030-69189-9_14
[26] Semerikov S O, Chukharev S M, Sakhno S I, Striuk A M, Iatsyshin A V, Klimov S V, Osadchyi V V, Vakaliuk T A, Nechypurenko P P, Bondarenko O V and Danylchuk H B 2022 *IOP Conference Series: Earth and Environmental Science* **1049**(1) 011001 URL https://doi.org/10.1088/1755-1315/1049/1/011001
[27] Karpenko O, Myrontsov M and Anpilova Y 2022 Application of Discriminant Analysis in the Interpretation of Well-Logging Data *Systems, Decision and Control in Energy III* ed Zaporozhets A (Cham: Springer International Publishing) pp 267–275 URL https://doi.org/10.1007/978-3-030-87675-3_16
[28] Kotsiuba I G, Skyba G V, Skuratovskaya I A and Lyko S M 2019 *Methods and Objects of Chemical Analysis* **14**(4) 200–207 URL https://doi.org/10.17721/moca.2019.200-207
[29] Skurativska I, Skurativskyi S, Popov O, Viktoriia D, Mykhliuk E and Dement M 2022 Complex Oxygen Regimes of Water Objects Under the Anthropogenic Loading *Systems, Decision and Control in Energy III* ed Zaporozhets A (Cham: Springer International Publishing) pp 317–334 ISBN 978-3-030-87675-3 URL https://doi.org/10.1007/978-3-030-87675-3_20
[30] Popov O, Iatsyshyn A, Kovach V, Artemchuk V, Kameneva I, Radchenko O, Nikolaiev K, Stanytsina V, Iatsyshyn A and Romanenko Y 2021 *Journal of Health and Pollution* **11**(31) 210910 URL https://doi.org/10.5696/2156-9614-11.31.210910

[31] Lysychenko G, Weber R, Kovach V, Gertsiuk M, Watson A and Krasnova I 2015 *Environmental Science and Pollution Research* **22** 14391–14404 URL https://doi.org/10.1007/s11356-015-5184-1
[32] Kulyk V, Burykin O, Malogulko J and Hrynyk V 2020 Anticipatory control of transit power flows from the renewable energy sources in electric power system *2020 IEEE 7th International Conference on Energy Smart Systems (ESS)* pp 123–127 URL https://doi.org/10.1109/ESS50319.2020.9160115
[33] Malogulko J, Kotylko I and N S 2020 *Przeglad Elektrotechniczny* **96**(10) 119–123 URL http://pe.org.pl/articles/2020/10/22.pdf
[34] Bogoslavska O, Stanytsina V, Artemchuk V, Garmata O and Lavrinenko V 2021 Comparative Efficiency Assessment of Using Biofuels in Heat Supply Systems by Levelized Cost of Heat into Account Environmental Taxes *Systems, Decision and Control in Energy II* ed Zaporozhets A and Artemchuk V (Cham: Springer International Publishing) pp 167–185 URL https://doi.org/10.1007/978-3-030-69189-9_10
[35] Kyrylenko O V, Pavlovsky V V and Blinov I V 2022 *Tekhnichna Elektrodynamika* **2022**(5) 59–66 URL https://doi.org/10.15407/techned2022.05.059
[36] Blinov I V, Trach I V, Parus Y V, Derevianko D G and Khomenko V M 2022 *Tekhnichna Elektrodynamika* **2022** 60–69 URL https://doi.org/10.15407/techned2022.02.060
[37] Bogoslavska O Y, Stanytsina V V, Artemchuk V O, Maevsky O V, Garmata O M, Lavrinenko V M and Zinovieva I S 2022 *IOP Conference Series: Earth and Environmental Science* **1049**(1) 012018 URL https://doi.org/10.1088/1755-1315/1049/1/012018
[38] Stanytsina V, Artemchuk V, Bogoslavska O, Zaporozhets A, Kalinichenko A, Stebila J, Havrysh V and Suszanowicz D 2022 *Energies* **15**(19) 7215 URL https://doi.org/10.3390/en15197215
[39] Shkitsa L, Yatsyshyn T, Lyakh M and Sydorenko O 2020 *IOP Conference Series: Materials Science and Engineering* **749**(1) 012009 URL https://doi.org/10.1088/1757-899X/749/1/012009
[40] Yatsyshyn T, Glibovytska N, Skitsa L, Liakh M and Kachala S 2020 Investigation of Biotechnogenic System Formed by Long-Term Impact of Oil Extraction Objects *Systems, Decision and Control in Energy I* ed Babak V, Isaienko V and Zaporozhets A (Cham: Springer International Publishing) pp 165–177 URL https://doi.org/10.1007/978-3-030-48583-2_11
[41] Popov O O, Iatsyshyn A V, Iatsyshyn A V, Kovach V O, Artemchuk V O, Gurieiev V O, Kutsan Y G, Zinovieva I S, Alieksieieva O V, Kovalenko V V and Kiv A E 2021 Immersive technology for training and professional development of nuclear power plants personnel *Proceedings of the 4th International Workshop on Augmented Reality in Education (AREdu 2021), Kryvyi Rih, Ukraine, May 11, 2021* (*CEUR Workshop Proceedings* vol 2898) ed Lytvynova S H and Semerikov S O (CEUR-WS.org) pp 230–254 URL https://ceur-ws.org/Vol-2898/paper13.pdf
[42] Semerikov S, Chukharev S, Sakhno S, Striuk A, Iatsyshyn A, Klimov S, Osadchyi V, Vakaliuk T, Nechypurenko P, Bondarenko O and Danylchuk H 2021 *E3S Web of Conferences* **280** 00001 URL https://doi.org/10.1051/e3sconf/202128000001
[43] Popov O O, Kyrylenko Y O, Kameneva I P, Iatsyshyn A V, Iatsyshyn A V, Kovach V O, Artemchuk V O, Bliznyuk V N and Kiv A E 2022 *CTE Workshop Proceedings* **9** 306–322 URL https://doi.org/10.55056/cte.122
[44] Gurieiev V, Kutsan Y, Iatsyshyn A, Iatsyshyn A, Kovach V, Lysenko E, Artemchuk V and Popov O 2020 Simulating Systems for Advanced Training and Professional Development of Energy Specialists in Power Sector *Proceedings of the 16th International Conference on ICT in Education, Research and Industrial Applications. Integration, Harmonization and Knowledge Transfer. Volume II: Workshops, Kharkiv, Ukraine, October 06-10, 2020* (*CEUR Workshop Proceedings* vol 2732) ed Sokolov O, Zholtkevych G, Yakovyna V, Tarasich Y, Kharchenko V, Kobets V, Burov O, Semerikov S and Kravtsov H (CEUR-WS.org) pp 693–708 URL https://ceur-ws.org/Vol-2732/20200693.pdf
[45] Kilnytskyi O 2018 Energy trends: which projects should be invested in. The landscape of the Ukrainian electricity market will change much faster than many people think URL https://mind.ua/publications/20190743-energetichni-trendi-v-yaki-proekti-varto-investuvati-koshti
[46] Miroshnychenko B 2021 Between “green” and Fukushima: is there a future in nuclear energy URL https://www.epravda.com.ua/publications/2021/12/13/680582
[47] Lutska V 2021 To close reactors or to build new ones: trends in the development of atomic energy in the world. While Germany is completely abandoning nuclear power plants, China is building a dozen new reactors URL https://hmarochos.kiev.ua/2021/02/04/zakryvaty-reaktory-chy-buduvaty-novi-tendentsiyi-rozvytku-atomnoyi-energetyky-u-sviti
[48] Didenko S 2021 Nuclear power: world trends and Ukrainian realities in the conditions of climate change URL https://cutt.ly/42TL08B
[49] Liou J 2021 What are Small Modular Reactors (SMRs)? URL https://www.iaea.org/newscenter/news/what-are-small-modular-reactors-smrs

[50] Popov O, Finin G, Ivaschenko T, Iatsyshyn A and Hrushchynska N 2023 Current State and Prospects of Smallmodule Reactors Application in Different Countries of the World *Systems, Decision and Control in Energy IV: Volume II. Nuclear and Environmental Safety* ed Zaporozhets A and Popov O (Cham: Springer Nature Switzerland) pp 3–21 URL `https://doi.org/10.1007/978-3-031-22500-0_1`
[51] National Renewable Energy Laboratory 2020 Nuclear–Renewable Synergies for Clean Energy Solutions URL `https://www.nrel.gov/news/program/2020/nuclear-renewable-synergies-for-clean-energy-solutions.html`
[52] Energyfacts 2020 GE Won Two Projects for the BWRX-300 Small Modular Reactor Design – Energy Facts URL `https://www.energyfacts.eu/ge-won-two-projects-for-the-bwrx-300-small-modular-reactor-design`
[53] Ontario Power Generation Inc 2021 Canada's first Small Modular Reactor project reaches significant milestone URL `https://www.opg.com/stories/canadas-first-small-modular-reactor-project-reaches-significant-milestone/`
[54] Semenov V, Shchepetina T and Popov S 2021 Development of small nuclear power plants: tasks and prospects URL `https://nangs.org/news/renewables/nuclear/razvitie-malykh-atomnykh-stantsij-zadachi-i-perspektivy`
[55] Gaspar M 2021 Technology Neutral: Safety and Licensing of SMRs URL `https://www.iaea.org/newscenter/news/technology-neutral-safety-and-licensing-of-smrs`
[56] Holtec International 2020 Holtec's SMR-160 Small Modular Reactor, Ten Years in Development, Enters USNRC's Licensing Process URL `https://cutt.ly/AwdlWqAv`
[57] Zabulonov Y L, Popov O O, Skurativskyi S I, Iatsyshyn A V and Molitor N 2022 *IOP Conference Series: Earth and Environmental Science* **1049**(1) 012015 URL `https://doi.org/10.1088/1755-1315/1049/1/012015`

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Development of recommendations for improving the radiation monitoring system of Ukraine

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Abstract. The effective functioning of the radiation monitoring network is an all-important task for all countries worldwide because the health of personnel working at radiation-hazardous facilities and the population living in the affected areas depend on it. A critical analysis of the functioning of radiation monitoring systems of various countries worldwide (Ukraine, United States of America, France, Sweden, Germany, South Korea, Switzerland, and China) was valid and showed their advantages and disadvantages. Criteria for displaying data on the electronic map about the state of radiation pollution and criteria for reports on the functioning of the radiation monitoring network have been determined. To improve the functioning of the radiation monitoring system of Ukraine, some recommendations for their improvement have been provided.

1. Introduction

Nowadays, many institutions and organizations worldwide use hazardous radiation technologies and sources of ionizing radiation in their activities (about 10 thousand enterprises in Ukraine, as of the end of 2021, were operating). Such objects include nuclear power plants (NPP), research reactors, specialized plants for processing and storing radioactive waste, enterprises extracting and processing uranium ores, and medical facilities using radioisotopes. Oil, gas, coal industry, and heat energy enterprises also participate in the radiation situation formation. During their operation, there is a noticeable redistribution of natural radionuclides (uranium, thorium, decay products, potassium, etc.) in the environment. In addition, fuel for nuclear power plants and spent fuel assemblies are transported through many territories. All these objects are objects of increased danger because emergencies related to their activities can lead to highly complex consequences for the present and future generations due to uncontrolled (accidents) or controlled (terrorist act) release of a significant number of radioactive substances into the environment.

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Therefore, one of the most critical components of the country's national security is the provision of nuclear and radiation safety.

In the territories where radiation-hazardous objects are in Ukraine, either non-automated sampling or stationary automated systems for monitoring the radiation situation are used for radiation monitoring. However, such approaches have some disadvantages: fieldwork is carried out, which poses a threat to humans in conditions of a significant level of radiation in the research territory; not equipment mobility of automatic systems doesn't allow assessment of radiation pollution levels across all studies territory. Furthermore, the non-automated sampling and stationary monitor posts don't allow to spend continuous environmental radiation monitoring in the part of a large square, resulting in information about the radiation situation in the research territory being released with a delay.

One of the main aspects of nuclear and radiation safety is radiation monitoring in the territories where hazardous radiation facilities are located, which various legal acts regulate. From that place, the effective functioning of radiation monitoring networks is an essential task for every country of the health of personnel working at hazardous radiation facilities and the population living in contaminated areas.

The legal acts regulate science publications, and information resources were analyzed in the research of the functionality of radiation monitoring networks. The result of analyzing showed that the problem outlined by us was considered and described in the following directions:

- construction of environmental monitoring networks [1–5];
- development equipment for radiation monitoring networks [6–10];
- development software for analysis and visualization monitoring data [11–14];
- using monitoring data for solving management by the radioactively contaminated territory [15–19].

Therefore, issues of ensuring nuclear and radiation security are looked up worldwide.

The aim is to determine the main advantage and disadvantages of radiation monitoring networks and to provide recommendations for their improvement in Ukraine.

2. Results

Radiation monitoring is an information and technical system of observation, assessment, and forecast of the radiation state of the biosphere. Radiation monitoring is a system of long-term repeated monitoring to assess the state of the radiation situation. Environmental radiation monitoring is a system of regularly monitoring the radiation state of the environment, migration, and accumulation of radionuclides, potentially dangerous phenomena, etc. The primary purpose of monitoring is to provide information to decision-makers.

We will list the main tasks of radiation monitoring [20, 21]:

- observation and control of the state of the territory contaminated with radionuclides, its hazardous parts, and the development of ways to reduce the danger from contamination;
- assessment of the state of objects in the environment according to the parameters that characterize the radioecological situation both in the zone of pollution and outside it;
- identification of trends in changes in the state of radioactive contamination of the environment in connection with the operation of radiation-dangerous objects, as well as during the implementation of radiological protection measures carried out in pollution territories;
- elucidation of possible trends to changes in the state of health of the population living in radionuclides-contaminated areas;
- information provision of the forecast of the radioecological situation in the radionuclides pollution territories and the country in general.

Next, we will analyze the existing monitoring system in Ukraine and compare it with similar systems in other countries. This will allow us to identify shortcomings and determine directions for its improvement.

2.1. Ukraine

To date, non-automated sampling or stationary automated systems for monitoring the radiation situation are used for radiation monitoring in the territories where radiation-hazardous objects are in Ukraine. However, the disadvantage of such approaches and means is, firstly, the need for physical participation of a person in sampling, which creates a significant risk for his health in conditions with a substantial level of radiation in the research territory, and secondly, the lack of mobility of the equipment of automated systems, which does not allow to assess the level of radiation pollution in the entire studied area. They must provide an opportunity to quickly respond to complex radiation environment conditions of limited access to the research object (fire, destruction of the thing, rugged terrain, significant vegetation). Also, non-automated sampling and stationary posts do not allow for continuous environmental radiation monitoring of large areas, for example, such as the Chornobyl Exclusion Zone (CEZ).

Today, radiation monitoring in Ukraine is carried out by various entities – SE "NAEK "Enerhoatom", the State Agency of Ukraine on Exclusion Zone Management (SAUEZM), the State Space Agency, the National Academy of Sciences, and the UkrHydromet Center (UkrHMDs) under the State Service of Ukraine for Emergency Situations (SSUES). However, their systems provide only sectoral observations of the radiation environment.

All received information about radioactivity is open to the public through the Integrated Network of Radiation Monitoring of the Environment (figure 1). You can find out with the help of the map: the radiation level, the location of the measurement point, and who provided the information.

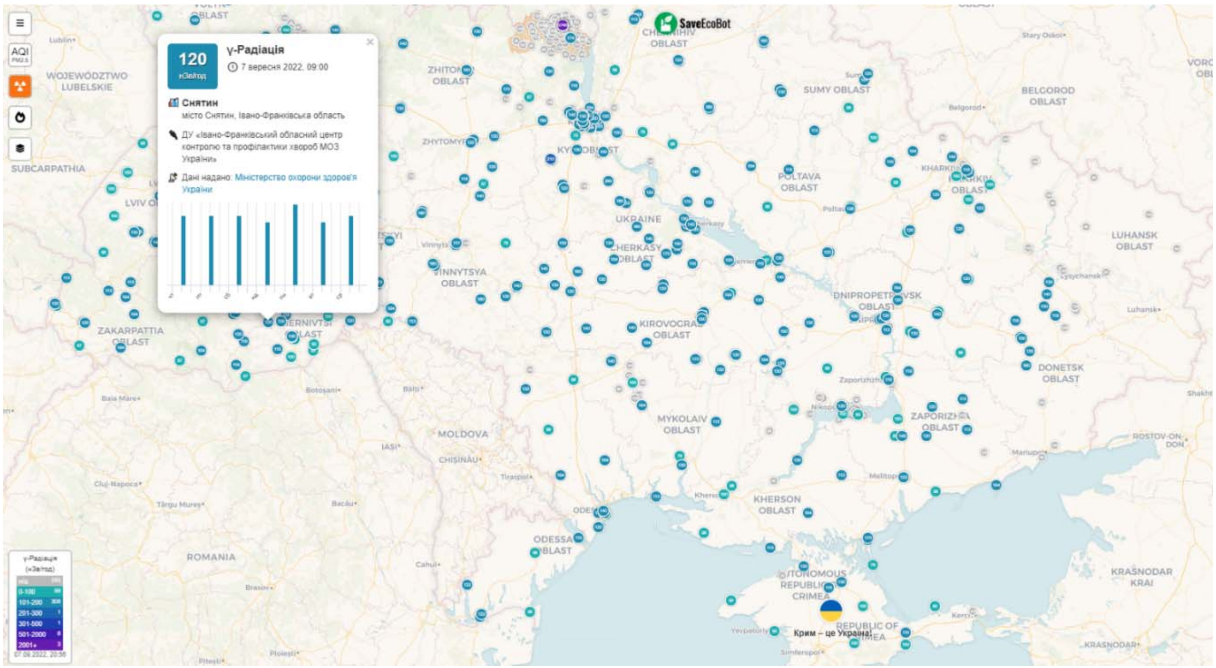

Figure 1. Map of the radiation background in Ukraine [22].

The Ukrainian Hydrometeorological Center of the SES of Ukraine (UkrHMC) monitors radioactive atmospheric pollution through daily measurements of gamma radiation exposure dose, deposition of radioactive particles from the atmosphere, and the content of radioactive aerosols in the air.

The UkrHMC measures radioactive contamination of surface water CS-137 and soil contamination and monitors gamma radiation exposure doses at ten automated points near NPPs. Furthermore, the UkrHMS monitors the concentration of radionuclides, radionuclides in atmospheric precipitation, and the concentration of 'hot' particles in the air within the 30-kilometer zone around the Chornobyl NPP (exclusion zone). In addition, the International Radioecological Laboratory of the Chornobyl Center for Atomic Safety, Radioactive Waste, and Radioecology Slavutych monitors the impact of radiation on biota in the exclusion zone [1].

The SAUEZM implements the state policy in the exclusion zone management, the zone of unconditional (compulsory) resettlement, overcoming the consequences of the Chornobyl disaster. The SAUEZM provides work on determining the radiation status of the exclusion zone, including the industrial site of the Chornobyl NPP, and the area of unconditional (mandatory) resettlement, compliance with radiation safety standards, conducting radioecological monitoring and radiation control in the territories and objects located within them; carry out a general assessment of the radiation situation in the region of zones that have experienced radioactive contamination, environmental radiation monitoring in this territory. At all NPPs, research is conducted on the content of radioactive substances in ecological objects in the areas where the NPP is located in the water of surface reservoirs, the atmospheric air, and the soil of nearby settlements.

2.2. The USA

The nationwide RadNet system was generated to observe environmental radiation pollution levels. System RadNet has tracked radiation levels from testings nuclear weapons and nuclear reactor accidents at Chornobyl NPP (Ukraine) and Fukushima NPP (Japan). During a radiological incident, government officials use RadNet data to help make science-based decisions about protecting the population. Besides, scientists use the RadNet state of radioactive air pollution monitoring data to help estimate the potential radiation dose to humans. Also, use metrological data during the estimated quantity [23].

RadNet has 140 stationary air monitors that run 24 hours a day during the week and collect data near-real-time gamma radiation measurements. Figure 2 shows RadNet static air monitoring locations and precipitation and drinking water sampling locations that reported data in 2020.

Under standard conditions, air monitors RadNet operates continuously, and samples of air, precipitation, and drinking water are analyzed on a planned schedule (table 1) [24]. In addition, during a radiological emergency, the United States Environmental Protection Agency (EPA) can deploy teams to conduct air monitoring and the environment.

Table 1. Sampling frequency of the system RadNet.

Medium	Sampling frequency	Testing frequency
Air filters	Continuous (real-time)	Continuous (real-time)
Precipitation	As rainfall, snow or sleet occurs	Monthly analysis of a composite sample
Drinking water	Quarterly	Quarterly

RadNet system data are available in databases and reports. In addition, EPA publishes analytical and monitoring results after checking to ensure they meet high-quality standards.

Envirofacts RadNet Database includes laboratory analysis results from air monitor filters, precipitation sampling, and drinking water. Also, this database is historical data about sampling

Figure 2. RadNet stationary air monitors [23].

milk. Finally, this database includes the current and historical data needed to estimate long-term environmental radiation trends [26].

As well United States Nuclear Regulatory Commission implements radiation pollution monitoring continuously in states in the USA, such as a sample of bioassay, alpha scans, a physical survey of the disposition of the materials and equipment, sampling or assessment levels to monitor air, surface water, and groundwater, soil, and sediment, equipment, and personnel [6].

2.3. France

On the national level, monitoring the dose equivalent rate is carried out on all territories of France (figure 4) laboratory in the Institut de radioprotection et de sûreté nucléaire (IRSN). The automated detectors represent proportional counters manufactured by BITT Technology (figure 5) [26].

The measurement of the monitors transmitted through a multiprotocol label switching virtual private network (MPLS VPN) or a direct contract between the IRSN and a telecommunications operator, or under the agreement between the IRSN and the Gendarmerie Nationale. The monitoring system ensures receiving of the measurement data in a Microsoft SQL Server database. Each measurement result is automatically compared to a sliding reference average of one week's data. In addition, the measurement automatically checks if it is within the acceptable variation range ±40 nSv/h of this average indicator. Nevertheless, in other cases, size has to be

Figure 3. Filters air radiation monitoring [25].

manually validated by the Téléray remote sensing system [26].

The monitoring system operates in real time. It includes redundancy, a recovery plan, and an agreed service commitment from the network operator. Monitoring of the public radiation dose (passive dosimetry) is carried out using about a hundred dosimeters. However, today monitoring is carried out more and more frequently using radio-photoluminescence (RPL) dosimeters (manufactured by the IRSN's dosimetry laboratory) [6]. The dosimeters are exchanged every three months.

The facility from nuclear fuel processing Orano La Hague has mobile equipment for monitoring discharges and the environment, whether on a routine basis or in other emergencies. Four autonomous trailers are equipped with the following sampling and measurement equipment:

- system for sampling aerosols with continuous alpha/beta measurement;
- probe for continuous measurement of the ambient gamma dose rate;
- mobile sampling equipment allowing samples pf bio-indicators (grass, soil, water).

The measurement data and report are sent in real-time to the correspondent department. Each trailer has an electrical generator and a lighting system.

2.4. Sweden

The Swedish Radiation Safety Authority (SSM) manages two telemetric networks for monitoring external gamma dose rates. A nationwide network consisting of 28 monitoring stations (figure 6) and a network comprised of 30 monitoring stations near nuclear power plants (figure 7) [27].

The monitoring stations operate autonomously and transmit data continuously to the network servers SSM. SSM manages the monitoring stations via special software and ensures supporting

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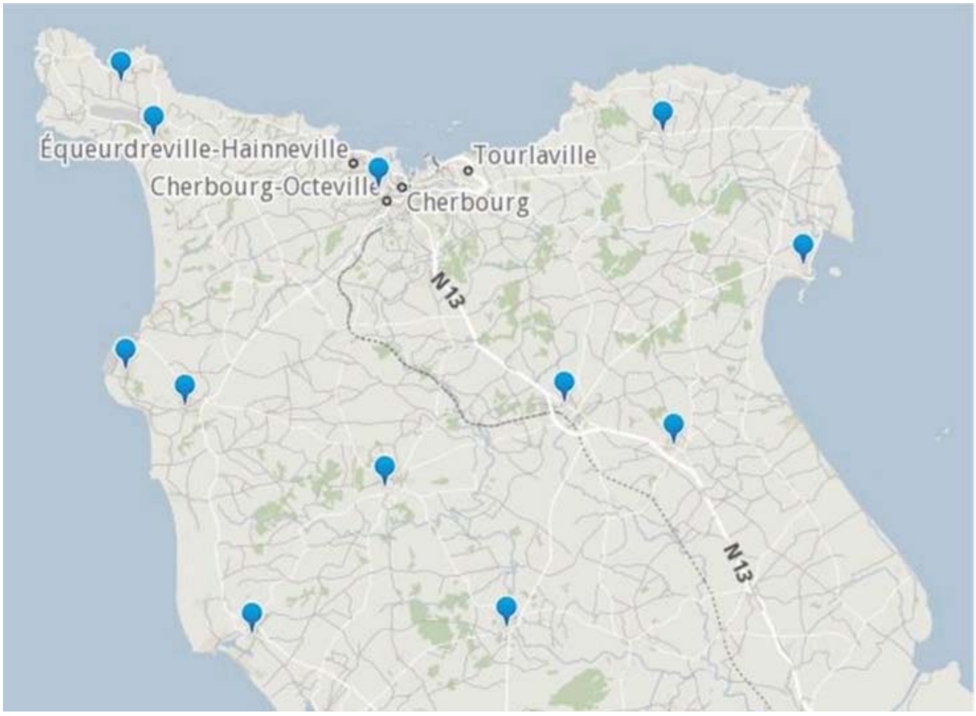

Figure 4. Locations of the IRSN [26].

Figure 5. BITT Technology detectors [26].

operations through collaboration with the administration in the NPP.

The prim y purpose of the nationwide network is to alarm if there is a significant increase above the natural background gamma radiation level and provide an instant overall picture of the radiation situation in Sweden. In addition, the purpose of monitoring networks NPP is to give an early indication of gamma radiation levels and plume direction following a nuclear accident with the release of radioactivity to the environment.

Both networks monitor ambient dose equivalent rate using monitoring probes equipped with

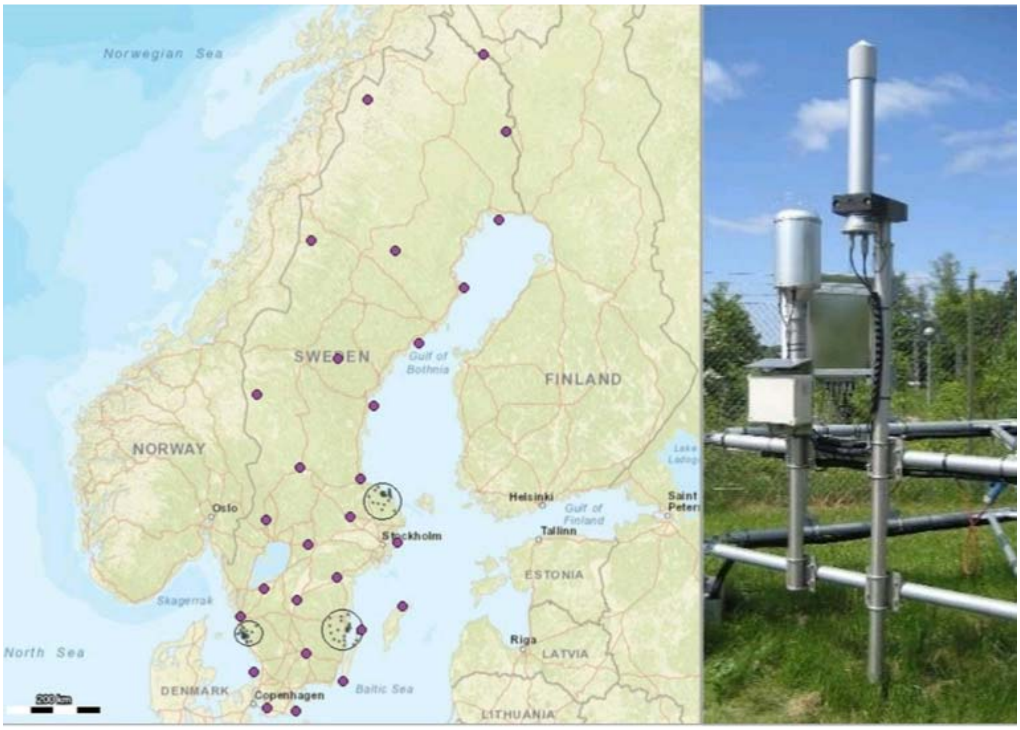

Figure 6. Location of the nationwide network of monitoring stations [27].

Figure 7. Location monitoring stations near NPPC [27].

three compensated Geiger-Muller tubes, enabling a measuring range of 10 nSv/h – 10 Sv/h for every monitoring station.

All monitoring stations use GammaTRACER XL2-3 (Bertin GmbH12, Germany) as a measuring device. The monitoring probes of the nationwide network are mounted on metrological stations, which are managed by Swedish Metrological and Hydrological Institute [28].

2.5. Germany

The German nationwide monitoring network (ADER) includes ∼1800 stationary probes equally distributed over the German territory with a typical distance of 20 km between them (figure 8). Their density is increased in the 25 km emergency planning zone around NPP. These additional probes are installed and operated by complementary networks from federal states. Data are exchanged between das Bundesamt für Strahlenschutz (BfS) and the local government and are carried out on a bilateral agreement. In the emergency regimen, data from all stations can be accessed almost in real-time, enabling the population's information to be efficient and prompt [29].

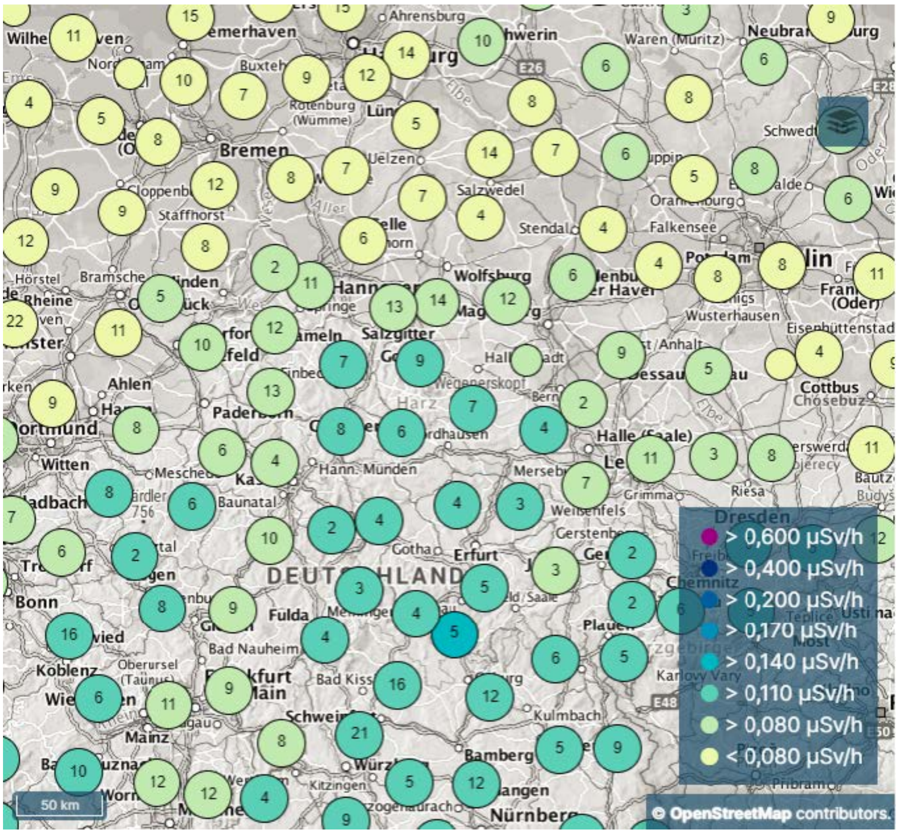

Figure 8. Probes location of radiation monitoring network [30].

The monitoring network is a part of the German "Integrated Measuring and Information System for the Surveillance of Environmental Radioactivity" (IMIS) and German national response plan, which considered the consequences of large-scale radioactive pollution of the environment. Moreover, data was transmitted to the European radiological data exchange platform (EURDEP) to aggregate a complete picture of European persons who accept decisions [31].

Ideally, monitoring stations ADER should be located on extensive flat grassland on undisturbed natural ground. In practice, two rules are used for the selection of new places for the installation of detectors. Firstly, probes must be installed at a height of 1 m on the flat natural ground (grassland) without disturbing buildings at a distance of 20 m. Secondly, considering neighboring stations, necessarily choose aimed at an almost homogeneous coverage of the German territory [31].

2.6. South Korea

The country operates 25 nuclear power reactors, a nuclear research reactor, nuclear fuel fabrication facilities, and radioactive waste disposal facility. Korean Institute of Nuclear Safety (KINS) is the only atomic safety regulatory expert organization that protects the public and the environment from the harmful effects of radiation. KINS, on behalf of the Korean government, conducted radiation monitoring around nuclear facilities and analyzed the relevant samples. Furthermore, local government around nuclear facilities have operated their radiation monitoring system [32].

The received information about radioactivity is open to the public via the Integrated Network of radiation monitoring of the environment (IERNet) (figure 9) [33].

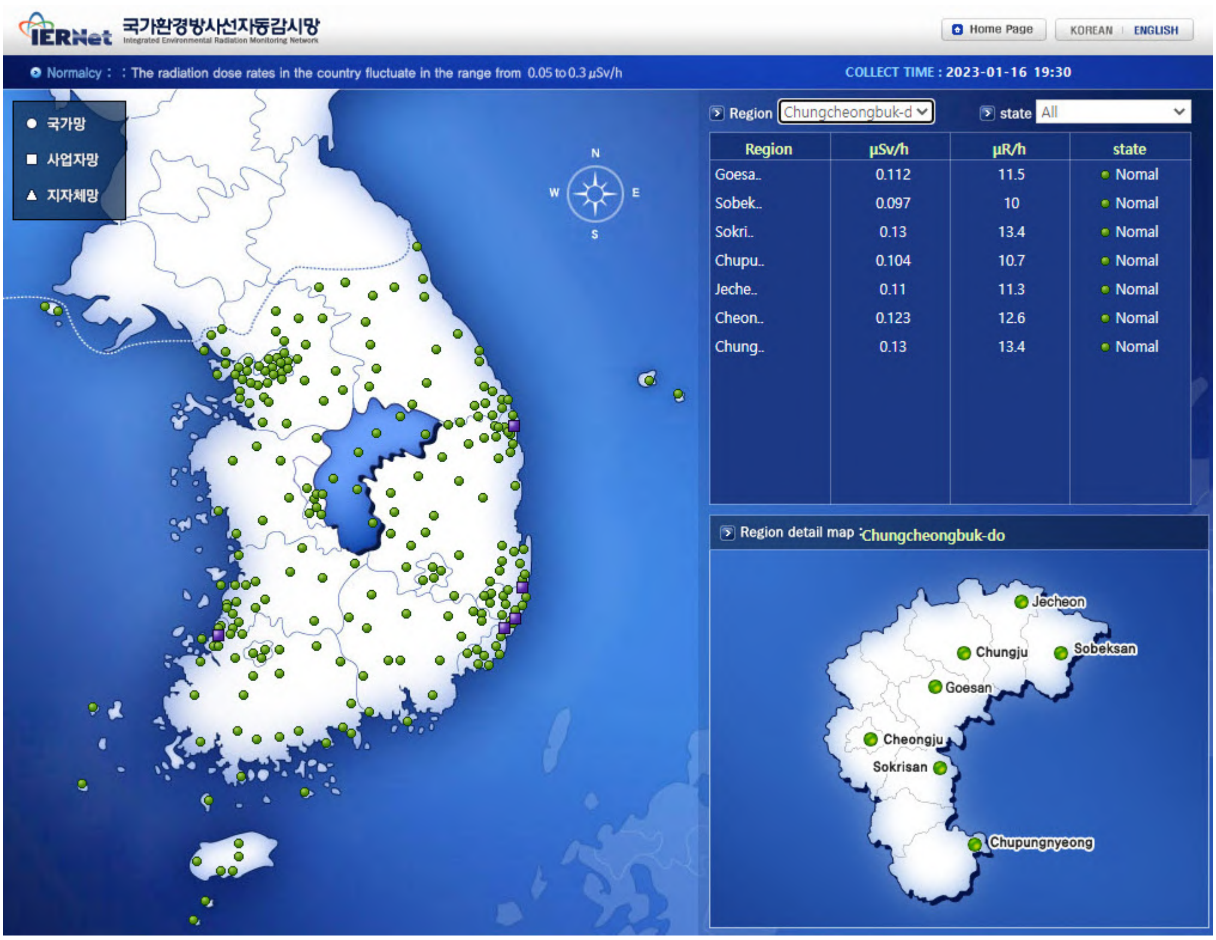

Figure 9. Integrated Network of radiation monitoring of the environment [33].

KINS introduced a mobile monitoring system mounted on vehicles to compensate for the mobility limitations of a fixed monitoring post. Monitoring systems monitor the surrounding areas where nuclear installations are located. That monitoring system can be used to monitor the radioactive plume formed during emergencies of various origins during the operation of these installations. The local government constantly compares the received data for reliability with the results of KINS. All local governments on the territory of which NPPs are located carry out weekly radiation monitoring using a mobile monitoring system. The resulting data are open to the public and are provided as core data for plans for identifying environmental radiation across the nation (SIREN).

2.7. Switzerland

National Emergency Operations Centre (NEOC) has its radioactivity monitoring network – NADAM. It consists of 76 stations, placed on the metrological stations MeteoSwiss in all territory of Switzerland (figure 10), that transmitted the measured values at ten-minute intervals to the NEOC [34].

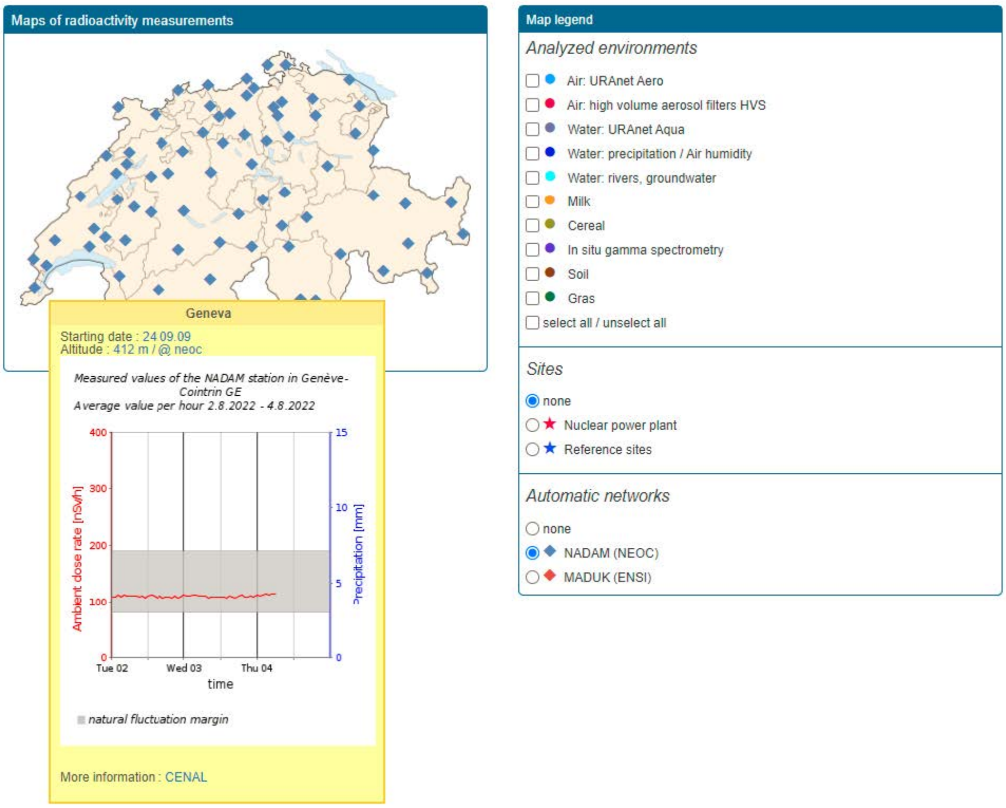

Figure 10. Swiss radiation monitoring system [35].

If the threshold value excessed 1000 nSv/h, an alarm is automatically raised. Depending on locations, the average daily values veer from 80 to 260 nSv/h. This is generally due to differences in the level of natural radiation.

At all stations NADAM, the part of artificial radiation amounts to only a few percent. The fake part mainly comes from the Chornobyl reactor accident in 1986 and the nuclear weapons test in the 1960s. The beginning of rain can lead to a temporary increase in the measurement values due to the natural radioactivity being rinsed from the air. The precipitation intensity and duration of the previous dry period are decisive here. In winter, the snow cover can decrease the part of ground radiation to such an extent that the measured values are below those observed in the long term [34].

2.8. *China*

Mainland China is building and exploiting 56 nuclear power units as of 31 March 2022; 38 are operating units. All data about NPP and environmental radiation monitoring can receive at the website `http://spi.mee.gov.cn:8080/spi` (figure 11).

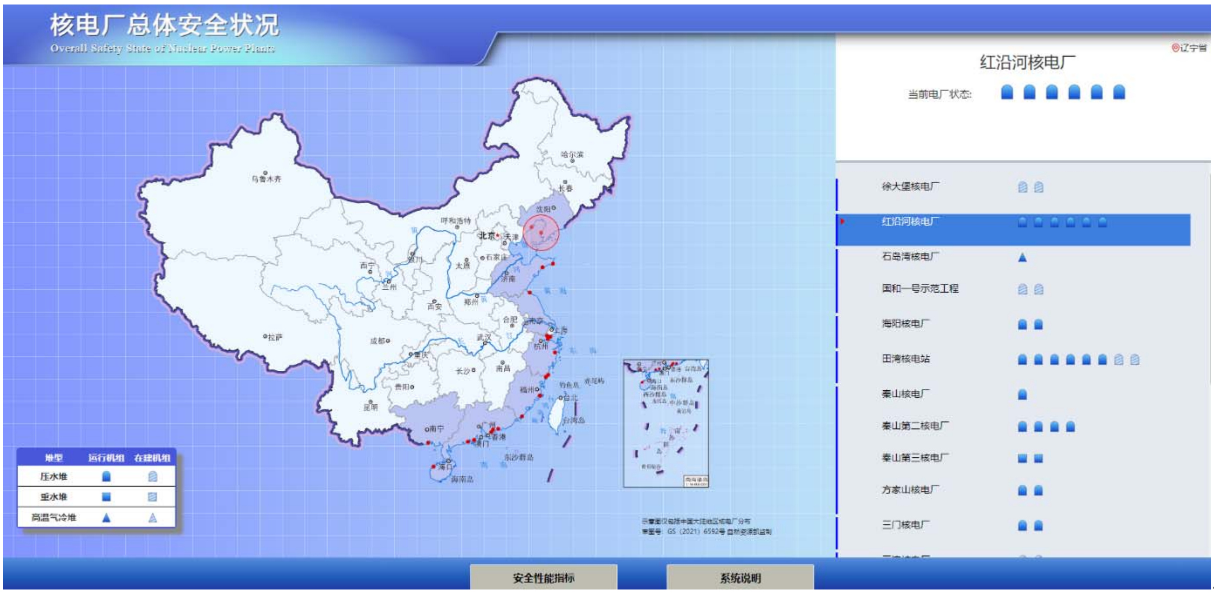

Figure 11. Information about the Chinese NPP location.

3. Discussion

To analyze and compare the nationwide monitoring systems of different countries, the criteria for displaying data on the electronic map about the state of radiation pollution were determined. The authors of the publication attributed to such measures (table 2):

1. Interface in national and English languages.
2. Meteorological data (direction, wind speed, humidity, air temperature, and atmospheric pressure).
3. The speed of updating the display of radiation monitoring data on the map.
4. Number of radiation monitoring networks posts.
5. Coverage density of the radiation monitoring network, m^2.
6. Availability of mobile radiation monitoring stations.
7. Coordinates of locations of stationary posts.
8. Coordinates of locations of radiation-hazardous facilities: NPP, research reactor, specialized plants for the processing and storage of radioactive waste, uranium ore mining and processing enterprises, medical facilities that use radioisotopes.
9. Availability and coordinates of radioactive monitoring stations of water bodies.
10. Availability of these stationary monitoring stations for atmospheric air pollution by chemical substances and dust of various fractions.
11. Ability to export monitoring data for a certain period to a separate file for an independent analysis.

Table 2. Criteria for a report on the functioning of the radiation monitoring networks.

Criteria	Countries							
	The USA	Sweden	France	Germany	South Korea	China	Switzerland	Ukraine
1.	+	+	+	+	+	−	+	+
2.	−	−	−	−	−	−	+	+
3.	daily	daily	daily	daily	daily	daily	daily	daily for most posts
4.	140	58	no data	1800	no data	around 29	76	no data
5.	70243	9111	-	199	-	330931	543	−
6.	Quantity unknown	Quantity unknown	4	Quantity unknown	Quantity unknown	Quantity unknown	Quantity unknown	Quantity unknown
7.	+	+	+	+	+	+	+	+
8.	−	−	−	−	+	+	+	−
9.	+	+	+	+	+	+	+	+
10.	−	−	−	−	−	+	+	+
11.	−	−	−	−	−	−	−	−

Each monitoring network is specific to a particular country, considering all its factors. Each country has information on the coordinates of the locations of stationary posts, and data on radiation pollution is updated daily. Unfortunately, the China map needs an interface in English, which complicates the data analysis process. We want to note that the highest coverage density of the radiation monitoring networks is in Germany; however, in some countries, information on the number of stationary posts was unavailable. As shown in table 2, all the studied countries have mobile radiation monitoring posts, but their number still needs to be determined, except for France. The availability of meteorological data and stationary monitoring stations for atmospheric air pollution by chemical substances and dust of various fractions was available in Sweden, Ukraine, and China. Also, exporting monitoring data for a certain period cannot be exported into a separate file for an independent analysis.

We also analyzed the availability of various reports on the functioning of the radiation monitoring networks of the countries mentioned above, which were found in public access. Accordingly, criteria were developed for the following reports (table 3):

1. Availability of materials in English.
2. Frequency of updating the report on the functioning of the radiation monitoring networks in the country.
3. The year of publication of the last general report on the functioning of the radiation monitoring networks in the country
4. Availability of information about radiation pollution from radiation-hazardous objects.

We want to note that over half of the countries have publicly available outdated reports (from 3-5 years). Notices provided by the International Atomic Energy Agency were public in English, while other pieces were available only in the national language and on other sites. In connection with the military actions in the territory of Ukraine, information about the actual state of operation of the radiation monitoring network is not displayed in open sources on the Internet, including at the NPP.

Table 3. Criteria for a report on the functioning of the radiation monitoring networks.

Criteria	Countries							
	The USA	Sweden	France	Germany	South Korea	China	Switzerland	Ukraine
1.	+	+	–	+	–	–	+	–
2.	Quarterly	Quarterly	Quarterly	Quarterly	Quarterly	Quarterly	Quarterly	No data
3.	2022	2019	2018	2017	2018	2021	2022	2021
4.	–	–	–	–	–	–	–	–

4. Author contributions

This section describes the contributions of each author to the research presented in this publication.

- *Andrii V. Iatsyshyn*: Idea, justification, and article outline; analysis of literature sources on environmental monitoring networks; analysis of Ukraine's existing monitoring system and identification of monitoring subjects; development of criteria for displaying radiation pollution data on the electronic map; recommendations for increasing the efficiency and information usefulness of Ukraine's radiation monitoring system.
- *Taras G. Ivaschenko*: Analysis of literature sources on using monitoring data to solve environmental safety management problems in radiation-contaminated territories; analysis of the work of the National Emergency Operations Center (NEOC) and weather stations MeteoSwiss (Switzerland) in the field of radiation safety; development of criteria for displaying radiation pollution data on the electronic map; recommendations for increasing the efficiency and information usefulness of Ukraine's radiation monitoring system.
- *Iryna V. Matvieieva*: Analysis of literature sources on the development of software for analysis and visualization of monitoring data; features of operation, construction, and transmission of measured data of the French radiation monitoring system network; features of the process and construction of environmental radiation monitoring networks in China and Hong Kong; development of criteria for displaying radiation pollution data on the electronic map.
- *Julia V. Zakharchenko*: Functions and role of the Swedish Radiation Safety Authority; principles of operation of Sweden's monitoring stations using special software; principle of operation of the German nationwide monitoring network, network density and its construction, transmission of monitoring data; analysis of the availability of various reports on the functioning of radiation monitoring networks of the countries considered in the publication, which were found in public access, and development of criteria for such statements.
- *Anastasiia M. Lahoiko*: Substantiation of the relevance of the research; analysis of literature sources on the development of equipment for radiation monitoring networks; analysis of the national monitoring system RadNet (United States of America), features of its construction and operation of the corresponding equipment; role of the Korea Institute of Nuclear Safety (KINS) in implementing state-level radiation monitoring, the functions and analysis of the Integrated Environmental Radiation Monitoring Network (IERNet); analysis of the availability of various reports on the functioning of radiation monitoring networks of the countries considered in the publication, which were found in public access, and development of criteria for such messages; recommendations for increasing the efficiency and information usefulness of the functioning of Ukraine's radiation monitoring system.

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5. Conclusions

One of the main aspects of nuclear and radiation safety is radiation monitoring in the territories where hazardous radiation facilities are located, which various legal acts regulate. Therefore, the effective functioning of radiation monitoring networks is an essential task for every country of the health of personnel working at hazardous radiation facilities and the population living in contaminated areas.

A critical analysis of the functioning of nationwide monitoring systems of various countries of the world showed that these systems have differences in their organization (density of coverage, technological and scientific support, transmission, processing, and display of data).

The criteria for displaying data on the electronic map about the state of radiation pollution and for reporting on the functioning of nationwide radiation monitoring networks, which showed the advantages and disadvantages of such systems, were defined.

Several recommendations are given for improving Ukraine's radiation monitoring systems for monitoring entities, which will increase their efficiency for information usefulness.

To improve the radiation monitoring systems of Ukraine, the authors suggest the following:

- to improve and optimize the notification system for receiving daily information;
- increase the coverage area of monitoring network posts to obtain more accurate information about radiation pollution;
- increase the number of mobile surveillance posts;
- on the electronic map, which displays the state of radiation pollution, indicate the coordinates of the locations of radiation-hazardous objects (NPP, research reactors, specialized plants for processing and storing radioactive waste, enterprises extracting and processing uranium ores, and medical facilities using radioisotopes);
- make it possible to export monitoring data for a certain period into a separate file for independent analysis;
- implement an interface of maps and reports in English to provide information to the broader masses;
- to update quarterly publicly available reports on the radiation status of the territory of Ukraine, including on the websites of relevant international organizations;
- to prove information on radiation pollution from radiation-hazardous objects.

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References

[1] Barbashev S V, Vit'ko V I and Kovalenko G D 2011 *Radiation monitoring in Ukraine: status, problems and ways to solve them* (Odesa: Astroprint)

[2] Kong Y C, Mak K L and Yung C H 2022 Summary of Environmental Radiation Monitoring in Hong Kong 2021 Technical Report on Environmental Radiation Monitoring in Hong Kong 42 Hong Kong Observatory Kowloon, Hong Kong URL https://www.hko.gov.hk/en/publica/rm/files/rm042.pdf

[3] Vindel J M, Valenzuela R X, Navarro A A and Zarzalejo L F 2018 *Atmospheric Research* **212** 227–239 URL https://doi.org/10.1016/j.atmosres.2018.05.010

[4] Gallego Manzano L, Bisegni C, Boukabache H, Curioni A, Heracleous N, Murtas F, Perrin D and Silari M 2020 *Radiation Measurements* **139** 106488 URL https://doi.org/10.1016/j.radmeas.2020.106488

[5] Popov O, Artemchuk V, Iatsyshyn A, Kovach V, Iatsyshyn A, Turevych A and Kutsenko V 2020 *Geochemistry of technogenesis* (4(32)) 86–95 URL https://doi.org/10.15407/geotech2020.32.086

[6] Institut de radioprotection et de sûreté nucléaire 2023 IRSN - French public expert in nuclear and radiological risks URL https://www.irsn.fr/EN/Pages/home.aspx
[7] American National Standards Institute 2013 N42.42-2012 - American National Standard Data Format for Radiation Detectors Used for Homeland Security URL https://ieeexplore.ieee.org/document/7331211
[8] Roy D K, Lal A, Sarker K K, Saha K K and Datta B 2021 *Agricultural Water Management* **255** 107003 URL https://doi.org/10.1016/j.agwat.2021.107003
[9] Marques L, Vale A and Vaz P 2021 *Sensors* **21**(4) 1051 URL https://doi.org/10.3390/s21041051
[10] Zabulonov Y L, Popov O O, Iatsyshyn A V, Iatsyshyn A V, Puhach O V and Stokolos M O 2022 *IOP Conference Series: Earth and Environmental Science* **1049**(1) 012013 URL https://doi.org/10.1088/1755-1315/1049/1/012013
[11] Pacific Northwest National Laboratory 2022 Software Engineering: Better software, faster URL https://www.pnnl.gov/software-engineering
[12] Royo P, Pastor E, Macias M, Cuadrado R, Barrado C and Vargas A 2018 *Remote Sensing* **10**(11) 1712 URL https://doi.org/10.3390/rs10111712
[13] Takahashi S, Sakurai D, Sasaki M, Miyamura H N and Sanada Y 2021 *The Visual Computer* **37**(12) 3039–3050 ISSN 1432-2315 URL https://doi.org/10.1007/s00371-021-02248-6
[14] Popov O O, Kyrylenko Y O, Kameneva I P, Iatsyshyn A V, Iatsyshyn A V, Kovach V O, Artemchuk V O, Bliznyuk V N and Kiv A E 2022 *CTE Workshop Proceedings* **9** 306–322 URL https://doi.org/10.55056/cte.122
[15] Ángeles Ontalba M, Ángel Corbacho J, Baeza A, Vasco J, Caballero J M, Valencia D and Baeza J A 2022 *Nuclear Engineering and Technology* **54**(2) 770–780 URL https://doi.org/10.1016/j.net.2021.08.007
[16] Li S, Wang H and Zhang Y 2021 *Nuclear Engineering and Technology* **53**(12) 4150–4157 URL https://doi.org/10.1016/j.net.2021.06.032
[17] Titov I E, Krechetnikov V V, Mikailova R A and Panov A V 2022 *Nuclear Engineering and Technology* **54**(6) 2244–2252 URL https://doi.org/10.1016/j.net.2021.12.017
[18] Šálek O, Matolín M and Gryc L 2018 *Journal of Environmental Radioactivity* **182** 101–107 URL https://doi.org/10.1016/j.jenvrad.2017.11.033
[19] Popov O, Bondar O, Ivaschenko T, Puhach O, Iatsyshyn A and Skurativskyi S 2023 Features of the Modern UAV-Based Complexes Use to Solve Radiation Control Problems *Systems, Decision and Control in Energy IV: Volume II. Nuclear and Environmental Safety* ed Zaporozhets A and Popov O (Cham: Springer Nature Switzerland) pp 35–57 URL https://doi.org/10.1007/978-3-031-22500-0_3
[20] International Atomic Energy Agency 2005 *Environmental and Source Monitoring for Purposes of Radiation Protection: Safety Guide No. RS-G-1.8* IAEA Safety Standards for protecting people and the environment (Vienna: International Atomic Energy Agency) URL https://www-pub.iaea.org/MTCD/Publications/PDF/Pub1216_web.pdf
[21] Gudkov I M 2016 *Radiobiology* (Kherson: Oldi-Plus)
[22] SaveEcoBot 2022 Karta radiatsiinoho fonu v Ukraini onlain: monitorynh radiatsii [Background Radiation Map Online: Radiation Monitoring] URL https://www.saveecobot.com/radiation-maps
[23] United States Environmental Protection Agency 2023 RadNet: Nationwide Environmental Radiation Monitoring URL https://www.epa.gov/radnet
[24] United States Environmental Protection Agency 2023 RadNet Sampling and Analyses Schedules URL https://www.epa.gov/radnet/radnet-sampling-and-analyses-schedules
[25] HI-Q Environmental Products Company, Inc 2022 RADNET – Environmental Air Radiation Monitor for Real-time Air Monitoring of Beta and Gamma Particulate Radionuclides URL https://www.hi-q.net/product/radnet/
[26] Tanner V and Ammel R V 2019 Environmental radioactivity monitoring arrangements Emergency radioactivity monitoring arrangements Tech. Rep. FR 18-01 European Commission, Directorate-General for Energy URL https://energy.ec.europa.eu/system/files/2019-04/art_35_technical_report_fr_18-01_0.pdf
[27] Tanner V, Peedo K and Diaconu E 2020 Environmental radioactivity monitoring arrangements Emergency radioactivity monitoring arrangements Tech. Rep. SE 19-03 European Commission, Directorate-General for Energy URL https://energy.ec.europa.eu/system/files/2020-08/art_35_technical_report_se_19-03_0.pdf
[28] Strålsäkerhetsmyndigheten 2022 National Metrology Laboratory URL https://www.stralsakerhetsmyndigheten.se/en/national-metrology-laboratory/
[29] Stöhlker U, Bleher M, Doll H, Dombrowski H, Harms W, Hellmann I, Luff R, Prommer B, Seifert S and Weiler F 2018 *Radiation Protection Dosimetry* **183**(4) 405–417 URL https://doi.org/10.1093/rpd/ncy154
[30] Federal Office for Radiation Protection 2023 Measuring stations in Germany URL https://odlinfo.bfs.de/ODL/EN/topics/location-of-measuring-stations/map/map_node.html

[31] Tanner V and Ryan A 2018 Routine and emergency radioactivity monitoring arrangements in Berlin Tech. Rep. DE 17-02 European Commission, Directorate-General for Energy URL `https://energy.ec.europa.eu/system/files/2018-07/art._35_technical_report_de_17-02_0.pdf`

[32] Joo H Y, Kim J W, Jeong S Y, Kim Y S and Moon J H 2020 Review of Technology Development Status of Mobile Radiation Monitoring Systems *Transactions of the Korean Nuclear Society Virtual Autumn Meeting. December 17-18, 2020* URL `http://surl.li/ejxld`

[33] Integrated Environmental Radiation Monitoring Network 2023 URL `https://iernet.kins.re.kr`

[34] Federal Office for Civil Protection FOCP National Emergency Operations Centre 2022 Measured radioactivity values URL `https://www.naz.ch/en/aktuell/messwerte.html`

[35] BAG/OFSP 2023 Maps of radioactivity measurements URL `https://www.radenviro.ch/access-to-data/?lang=en`

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PAPER • OPEN ACCESS

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Development of mathematical decision-making support tools for effective response to emergencies during the transportation of dangerous substances by road transport

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Abstract. Every year, the world sees an increase in the volume of hazardous goods transported by road. However, emergencies may arise related to the depressurization of containers (tanks, containers, cylinders, etc.) during the transportation of dangerous goods under various circumstances (traffic accidents, natural disasters, acts of terrorism, etc.). Furthermore, it can cause the ingress of hazardous chemicals into the environment and create significant risks for the population of the surrounding areas and habitat. The existing methods for assessing chemical accident consequences need to be revised. Therefore, they are not practical tools for solving problems of prompt response to emergencies associated with accidents while transporting dangerous substances by road transport. Unlike the existing ones, the authors developed new mathematical tools that consider all the main factors. They allow for determining the area of the affected zone, forecasting changes in its scale, and assessing risks to public health due to such emergencies. Comparison of the simulation results with the field measurements data showed high accuracy of the developed mathematical support.

1. Introduction

Hazardous materials are flammable, explosive, poisonous, corrosive, infectious, or radioactive products, for example, gasoline, fuel oil, oil, and chemicals. The most harmful substances are a fundamental part of our daily life and industrial development despite the characteristics of these materials [1].

Approximately 4 billion tons of harmful substances are transported worldwide annually, according to [2]. The demand for hazardous materials in the United States is 3 to 4 billion tons each year. These materials are widely used in manufacturing, agriculture, medicine, and other industrial areas. In China, approximately 95% of hazardous substances are transported from manufacturers to customers by road transport [1]. Between 77.000 and 88.000 million tons of dangerous goods were transported by road within the European Union from 2009 to 2013 [3]. The authors [4] investigated 1932 accidents that occurred worldwide while transporting hazardous substances by road and rail from the beginning of the 20th century to July 2004. They showed that more than half of the accidents occurred on roads.

Danhighwayss traffic accidents are still considered low-probability compared to more frequent and highly unpredictable natural hazards despite the above facts. In addition, this type of accident is classified as an accident with significant consequences which can seriously affect the population and environment.

Analysis of the sources shows that several incidents during the transportation of harmful substances are deficient. Nevertheless, accidents occur, and some of the consequences are very serious. For example, in November 2005, there was an accident in Sinaloa (Mexico) with a truck transporting ammonia.Thirty-nine9 people died as a result of the accident [5]. More than 30 accidents related to the transportation of dangerous substances by road occur annually in China, according to statistics A truck [6]. Truck with liquefied natural gas crashed on the highway in front of the tunnel and overturned in Hunan Province on October 6, 2012. Five people died, and two more were injured, including three firefights, due to the explosion. In 2013, a truck carrying fireworks ahead of Chinese New Year celebrations exploded and destroyed part of an overpass in China's Henan province and killed several people.

It is necessary to consider population density, traffic jams, and road closures while transporting harmful substances in urban areas. City traffic accidents can cause catastrophic human losses due to the high population density. Truck with chlorine collided with another vehicle in a metropolitan area of Nanjing, China, on March 29, 2005. It caused the death of 29 people and the evacuation of more than 10000 people. In October 2020, an 18-wheeler with 5000 gallons of sodium hydrosulfide (an extremely corrosive and toxic substance) overturned downtown Birmingham, England [7] (figure 1). In figure 2 shows a tanker truck accident in New Jersey that spilled 3000 gallons of fuel onto the roadway (February 2019).

Therefore, emergencies may arise related to the depressurization of containers (tanks, containers, cylinders, etc.) during the transportation of dangerous goods under various circumstances (traffic accidents, natural disasters, acts of terrorism, etc.). Furthermore, it can cause the ingress of hazardous chemicals into the environment and create significant risks for the population of the surrounding areas and habitat.

The studies [9,10] consider the risk of dangerous substances transportation as a measure of the probability and severity of damage to the population's health and components of the surrounding natural environment due to potential undesirable events. The risk from transporting harmful substances can be divided into two parts: the probability of an accident and the consequences if it occurs. Reniers et al [11] developed a risk assessment methodology for moving hazardous materials. They divided routes into smaller segments using multi-criteria analysis and assessing the likelihood of accidents involving dangerous vehicles leading to fatalities. The work [12] is aimed at determining the impact of hazardous traffic accidents on people with disabilities. It is done to provide the knowledge base necessary for creating competent disaster preparedness procedures. The article [1] contains a model built to reduce risks of transportation of harmful substances and transportation costs, considering several restrictions. This model was tested on a realistic example of transporting hazardous substances in the densely populated metropolitan

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Figure 1. Accident in Birmingham (October 2020) [7].

Figure 2. Tanker truck crash in New Jersey [8].

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area of Shanghai (China).

Popov et al [13, 14] considered several methods used to assess the situation in the case of accidents related to the spill (emission) of dangerous chemicals from technological containers on road transport. Their shortcomings were identified. It was also established that these methods are not practical decision-making support tools for the prevention and rapid elimination of the consequences of such emergencies. Therefore, developing new mathematical and software tools better than existing analogs in all leading indicators is an urgent and essential scientific problem.

The research aims to develop mathematical tools for assessing the consequences of accidents while transporting dangerous substances by road transport.

2. Development of mathematical means

The developed mathematical means of risk assessment should take into account the realities of the current situation during transporting of chemically hazardous substances (CHS) by road transport, possible types of accidents or partial depressurization, for example, as a result of terrorist acts. We used studies [15–17] to build such tools. Those studies most adequately describe the consequences of forecasting chemical accidents during transportation by road transport of the CHS.

Potential chemical risk in the vicinity of an accident of a mobile chemically hazardous object and the settlement zone near such an object is determined by the formula:

$$\mathrm{R}_x = \sum_{i}^{m} \mathrm{Q}^* \times \mathrm{P}_i \times \mathrm{R}_i, \tag{1}$$

where,

Q^* – case frequency during the year;

P_i – the probability of a person living in the i-th habitat (tables 1, 2);

R_i – conditional probability of injury to a person in the i-th habitat.

Table 1. Average daily distribution of the urban population by place of residence [16].

Time of day, hour	Residential and public buildings	Production buildings	In transport			Outside		
			Cities with a population (million people)					
			0.25... 0.5	0.5... 1.0	More than 1.0	0.25... 0.5	0.5... 1.0	More than 1.0
1...6	0.94	0.06	-	-	-	-	-	-
6...7	0.74	0.06	0.07	0.09	0.12	0.13	0.11	0.08
7...10	0.22	0.5	0.09	0.11	0.17	0.19	0.17	0.11
10...13	0.28	0.52	0.06	0.07	0.1	0.14	0.13	0.1
13...15	0.45	0.37	0.04	0.04	0.07	0.14	0.14	0.11
15...17	0.27	0.49	0.08	0.09	0.13	0.15	0.15	0.12
17...19	0.45	0.24	0.1	0.12	0.15	0.2	0.18	0,15
19...24	0.77	0.14	0.04	0.04	0.06	0.05	0.05	0.03

Currently, the occurrence frequency of dangerous event Q_j^* is calculated by the methods of risk theory or according to statistical data.

The occurrence frequency of dangerous event Q_j^* can be determined using the theory of expert evaluations. Expert assessments of the frequency of technogenic accidents are carried out taking into account their distribution into five levels:

Table 2. Average daily distribution of the rural population by place of residence [16]

Time of day, hour	Field and agricultural production		Residential buildings	
	During the day	At night	During the day	At night
1...6	0.25	0.1	0.75	0.9
6...7	0.6	0.4	0.4	0.6
7...10	0.75	0.75	0.25	0.25
10...13	0.8	0.8	0.2	0.2
13...15	0.85	0.75	0.15	0.25
15...17	0.85	0.5	0.15	0.5
17...19	0.8	0.4	0.2	0.6
19...24	0.5	0.2	0.5	0.8

– frequent failure: > 1 year^{-1};
– probable failure: $1 \ldots 10^{-2}$year^{-1};
– possible failure: $10^{-2} \ldots 10^{-4}$year^{-1};
– rare failure: $10^{-4} \ldots 10^{-6}$ year^{-1};
– almost impossible failure – expected frequency of occurrence $< 10^{-6}$ year^{-1}.

The probability of people being in the i-th environment P_i is determined based on the production activity of personnel. Therefore, calculation of the conditional probability of damage or mathematical expectation of injuries from the negative impact of CHS presents specific difficulties. These difficulties are related to the toxic effect on humans of different types of CHS. It is based on their physical and chemical properties and other exposure times depending on the presence in the zone of possible chemical damage.

The conditional probability of damage in the case of being in the zone of chemical injury is mainly determined by the location of damage, considering the height of the cloud rise. The site is formed due to the spread of the affected cloud to the residential part of the settlement in the braking area and the area of the emergency stop of transport from CHS and can be defined as [15]:

$$R = \frac{\mathrm{S}_B + \mathrm{S}_F}{\mathrm{S}_S}, \tag{2}$$

where,

S_B – area of the threshold chemical damage in the braking zone, km^2;

S_F – area of the threshold chemical damage in the size of the emergency stop of transport with CHS, km^2;

S_S – area of the settlement, km^2.

The area of the threshold chemical damage in the braking zone and the size of the emergency stop is determined by the depth of the threshold damage in these areas.

The area of chemical damage in the braking zone can be calculated by the following formula taking into account the rise of the affected cloud [15]:

$$\mathrm{S}_B = \sum_{i=1}^{n} \mathrm{S}_{B_i} \times \frac{\mathrm{H}_C}{\mathrm{H}_B}, \tag{3}$$

where,

S_B – an area of chemical damage in the i-th braking zone, It is defined as:

$$S_B = \frac{\pi\varphi}{360^\circ}[D_B + (D_{l_i} - D_B) \times k_m]^2 - D_B^2, \tag{4}$$

where,
D_B – distance from the building beginning to the road, m;
D_{l_i} – depth of the threshold lesion at the i-th braking zone, m;
l – is corresponded to the section of the final braking route to the emergency stop, m;
$l = 1$ – is compared to the braking route area when $D_l = D_{B,}$, m;
k_m – coefficient of spread reduction of the affected cloud depending on the building and number of floors of the buildings. It is defined in the paper [15].

The area of chemical damage in the emergency stop zone can be calculated by the formula taking into account the growth of the affected cloud,

$$S_F = \frac{\pi\varphi}{360^\circ}\left[[D_b + (D_{n_i} - D_b) \times k_m]^2 - D_B^2\right] \times \frac{H_C}{H_B}, \tag{5}$$

where,
D_{n_i} – depth of the threshold damage in the emergency stop zone;
φ – spread angle of possible chemical damage. It is determined according to table 3.
H_C – the height of the cloud threshold elevation, m;
H_B – the size of buildings in the settlement, m.

Table 3. Angular dimensions of zones of actual chemical damage

Degree of vertical stability	Inversion	Isometry	Convection
	Steady wind		
φ, degree	11.5	14.5	48.5
	Unsteady wind		
	47	48	69

Thus, determining the threshold depth, lethal chemical damage, and height of their cloud rise are essential in calculating the conditional probability of damage during such events.

The formula determines the length of the spill section before the damaged vehicle stops:

$$L_S = V_D t_{rd} + L_{mn}, \tag{6}$$

where,
V_D – speed of transport at the moment of depressurization, km/h;
t_{rd} – driver reaction time (0.3–1.7 sec);
L – braking distance. It is defined as [16]:

$$L_{mn} = V_D t_b + V_D^2/2\alpha_{max}, \tag{7}$$

where,
t_b – brake system activation time 0.3-0.5 sec;
α_{max} – maximum acceleration (deceleration) of transport, m/s^2, α_{max}=gK_g (g=9.81 m/s^2)
K_g – coefficient of tire adhesion of transport with the road surface. For vehicles in dry weather conditions, K_g≈0.5; during the rain K_g≈0.25.

Assessment of the reliable width of the CHS spill and its height (thickness) of the spill hl in the braking zone has great importance. In addition, the amount of CHS will determine if it spilled in this area, ultimately affecting the depth of chemical damage.

The accepted assumption in the existing methods is that determination of the CHS spill width is equivalent to the spill of petroleum products (1 liter of liquid is spilled on 0.15 m^2 of the road). A statement that h_l=0.05 m is incorrect in emergency braking due to the small amount of spilled CHS with a small depressurization on a relatively long braking distance. Based on this, it is necessary to determine the height of the CHS spill on the underlying surface, taking into account the spill area's width and length and the CHS's density. However, this is different based on the various physical and chemical properties of CHS.

One of the main parameters affecting the depth of the secondary damage cloud as an accident result at the chemically hazardous facility with a CHS spill is the area of the spill, the height of the liquid layer (thickness of the spill film), and degree of infiltration of CHS into the underlying surface. However, determining the actual spill area of CHS is somewhat complicated due to the wide range of CHS. In addition, such substances have different physical properties. So, the liquid layer's thickness may differ and depend on the type of underlying surface [18].

The correction coefficients of the spreading surface $\mathrm{K}_{n.xy}$ and infiltration K_{in} are one of the ways to solve the problem of the influence of the nature of the CHS spill and the degree of its penetration into the underlying surface. Such coefficients were obtained experimentally.

Prompt determination of the spill area plays a crucial role in the decontamination (disinfection) of the territory in the case of an accident with the CHS spill. The spill area of CHS S_{l_xy} can be defined by the formula taking into account the experimentally determined $\mathrm{K}_{n.xy}$:

$$\mathrm{S}_{l\_xy} = \pi\left(3.018\mathrm{V}_y^{0.393}\vartheta_y^{-0.116}\mathrm{t}_l^{0.115}\mathrm{K}_{n.xy}\right)^2, \tag{8}$$

where,

V_y – the volume of spilled CHS of y-the type, m^3;

ϑ_y – kinematic viscosity coefficient CSH of y-the kind, m^2/s;

t_l – fluid spreading time, min.

The height of spilled CHS y-the type on the underlying surface of the x-the type h_{l_xy}(m) can be defined taking into account S_{l_xy} using the formula:

$$\mathrm{h}_{l\_xy} = \frac{\mathrm{m}_y}{\rho_{ly} \cdot \mathrm{S}_{l\_xy}}, \tag{9}$$

where,

m_y – mass of spilled CHS on the underlying surface of a y-th type, kg;

ρ_{ly} – CHS density y-the type, kg/m^3.

The formula determines the evaporation time (striking action) of CHS:

$$\mathrm{T}_{\nu d} = \frac{\mathrm{h}_l \cdot \rho_l}{\mathrm{K}_2\mathrm{K}_4\mathrm{K}_7}, \tag{10}$$

where,

K_2, K_4, K_7 – coefficients according to [15].

The amount of liquid CHS in the braking zone m_b is determined by the formula taking into account the fraction of infiltration during the shedding to stop the damaged transport:

$$\mathrm{m}_b = \int_0^{\mathrm{t}_{nm}} G(t)dt = \mathrm{K}_{in}\left(\mathrm{G}_0 \cdot \mathrm{t}_{nm} - \frac{\rho_{ly} \cdot g \cdot \mu^2 \cdot \mathrm{S}_{ot}^2}{2\mathrm{S}_s} \cdot \mathrm{t}_{nm}^2\right), \tag{11}$$

where,

K_{in} – infiltration coefficient;

G_0 – mass consumption at the initial point in time (kg/s) is determined by the formula [19] for small quantities of depressurization area:

$$G_0 = \mu \cdot \rho_l \cdot S_{ot} \sqrt{2g(h_0 - h_{ot})}, \tag{12}$$

$t_{he} = t_{rd} + L_{nm}/V_b$ – CHS spilling time from the moment of depressurization of the capacity to stopping damaged transport;

V_b – averaged braking rate that is defined as $V_D/2$, m/s;

μ – spilling coefficient 0.6 – 0.8;

S_{ot} – hole area, m^2;

S_s – cross-sectional area;

h_0 – the initial height of the liquid column in the vessel, m;

h_{ot} – hole height, m.

Stop of transport leads to a spill of CHS rest contained in the tank: or until it is over at $h_{ot} = 0$, or partially (at $h_{ot} > 0$), or up to the time of sealing the hole.

The amount of spilled CHS is defined by the formula taking into account the proportion of infiltration m_2 after stopping the damaged transport:

$$m_2 = K_{in} \left(\mu \cdot \rho_l \cdot S_{ot} \sqrt{2g(h_0' - h_{ot})} \cdot t_F - \frac{\rho_l \cdot g \cdot \mu^2 \cdot S_{ot}^2}{2S_s} \cdot t_F^2 \right), \tag{13}$$

where,

t_0 – time of CHS spill after vehicle stops, min;

$h_0{}'$ – the initial height of the liquid column in the tank from the moment of stopping the transport is defined by the formula [20]:

$$h_0' = h_0 - \frac{\mu \cdot S_{ot}}{S_s} \sqrt{2g(h_0 - h_{ot})} \cdot t_{nm} + \frac{g \cdot \mu^2 \cdot S_{ot}^2}{2S_s^2} \cdot t_{nm}^2, \tag{14}$$

Generally, S_S can be calculated as follows [5]

$$S_S = \int_0^{t_{nm}} 2l \sqrt{h_0'(t) \cdot \left[D - h_0'(t) dt\right]}, \tag{15}$$

At short-term spill it can be defined as:

$$S_S = 2l \sqrt{h_0(D - h_0)}, \tag{16}$$

A long-term spill can be defined as:

$$S_S = l \left[\sqrt{h_0(D - h_0)} + \sqrt{h_0'(D - h_0')} \right], \tag{17}$$

where,

$h_0{}'$ – values of the liquid column in the tank for a specific time of the spill, m;

l – tank length, m;

D – tank diameter, m.

The formula defines the time of entire spill through a small hole nm:

$$t_{nm} = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} \tag{18}$$

The amount of spilled CHS in the emergency stop area with the complete ending (destruction) of the capacity taking into account the fraction of infiltration, is defined as:

$$m_F = K_{in} \cdot (Q_0 - m_b) \tag{19}$$

The following formula calculates the depth of chemical contamination:

$$D_c = min(D_n(D_D); D_{fr}), \tag{20}$$

where

$$D_n = 0,95 \cdot \sqrt[l+b+d]{\frac{m}{0,13(2\pi)^{\frac{3}{2}} \cdot a \cdot c \cdot C_n}} K_B \cdot K_t, \tag{21}$$

For lethal cases

$$D_D = 0,95 \cdot \sqrt[l+b+d]{\frac{m}{0,13(2\pi)^{\frac{3}{2}} \cdot a \cdot c \cdot C_D}} K_B \cdot K_t, \tag{22}$$

where

m – CHS mass taking into account the fraction of infiltration, kg;

C_n, C_D – the value of the threshold and fatal cases for CHS is considered respectively, g/m^3;

K_B, K_t – dependence of depth damage on wind speed and coefficient of exposure to air temperature to the depth;

$a,\ b,\ c,\ d$ – coefficients of the steppe variance models determined according to [5];

The formula defines D_{fr}:

$$D_{fr} = U_n \cdot T_{\nu d}, \tag{23}$$

where

U_n – transfer rate of the cloud front at the given wind speed data and degree of vertical stability of the air, km/h, is determined according to [15];

$T_{\nu d}$ – time of the dramatic action determined by the formula 10.

The height of the lifting cloud for the limited degree of damage, taking into account sheltering of the population in buildings, is determined by the formula:

$$H_n = c \cdot D_n \sqrt{2ln \frac{m \cdot \rho_a (1 - e^{-k_1 \cdot t_{loc}})}{\rho_g \cdot 0,13 \cdot (2\pi)^{\frac{3}{2}} C_n \cdot a \cdot c \cdot D_n^{1+b+d}}}, \tag{24}$$

for lethal cases

$$H_D = c \cdot D_D \sqrt{2ln \frac{m \cdot \rho_a (1 - e^{-k_1 \cdot t_{loc}})}{\rho_g \cdot 0,13 \cdot (2\pi)^{\frac{3}{2}} C_{cm} \cdot a \cdot c \cdot D_D^{1+b+d}}}, \tag{25}$$

where,

p_a,p_g – air and gas density of the appropriate type of CHS respectively, kg/m^3;

t_{loc} – time of localization of the accident;

k_1 – a multiplicity of air exchange in premises of the building, h^{-1};

k_2 – coefficient of the wind speed value;

k_T – ambient air temperature coefficient.

Estimated air temperatures and air exchange requirements in the premises are described in detail in [21].

It should be noted that the disadvantage of the proposed mathematical means is in finding input data. It requires depressurization area to calculate the mass of the spilled CHS by the formula 6.

Calculations were made and compared with full-time measurements to evaluate the accuracy of the proposed mathematical means with the results of other techniques used on the example of an accident occurring in October 2020 at the Birmingham Center (England) [7,22]. Input: there was a tanker depressurization with sodium hydrosulfide, 5000 gallons = 22.73 m^3, the hole was 0.04 m^2 in the bottom, the initial height of the liquid column was 1.5 m, the speed of movement of vehicles was 60 km/h, there was no precipitation inversion, the air temperature was $+15^oC$, the wind speed was one m/s, elimination time was 450 min. Results of calculations of the CHS spilled area on the underlying surface and depth of chemical damage are presented in table 4.

Table 4. Comparison of the calculations results of the CHS spilled area on the underlying surface and the depths of chemical levels defined in various ways.

	Method [23]	Method [24]	Method [25]	Model [15]	Model [16]	Author model	Field measurement
Spill area, m^2	268	280	482	436	323	347	370
δ, %	28	24	30	18	13	6	-
Depth of chemical damage, m	952	985	1476	1347	1130	1158	1246
δ, %	24	21	18	8	9	7	-

The table shows that mathematical models of pollution of the earth's surface and air as a result of the accident during CHS transport by road allow us to determine the necessary parameters of the damage zone with high accuracy. A significant advantage of such models is that, unlike other methods, they take into account: the nature of the underlying surface; the absorption of hazardous chemicals in case of an accident; the parameters of the spill area for various hazardous chemicals.

Subsequently, it is planned to develop a software-modeling complex based on the results obtained. The complex will become an effective tool for supporting management decisions on a prompt response to such situations to ensure a high level of protection of the population and environment, minimize the extent of damage, and ensure the effective elimination of appropriate consequences.

3. Author contributions

The research results presented in this publication are a collective effort of the individual authors:

- **Andrii V. Iatsyshyn** contributed to the conception and design of the study, analyzed the literature, reviewed incidents in Birmingham (October 2020) and New Jersey (February 2019), determined the quantity of chemically hazardous substances in the braking area, and assessed the reliability of the proposed mathematical tools.
- **Liudmyla M. Markina** evaluated the potential chemical risk in the vicinity of the accident and settlement zone, determined the average daily distribution of urban and rural population by place of stay, and assessed the reliability of the proposed mathematical tools.
- **Olha O. Tiutiunyk** determined the main parameters affecting the depth of secondary damage cloud as a result of an accident at a chemically hazardous facility, determined the initial height of liquid column in the tank at the moment of transport stoppage, and assessed the reliability of the proposed mathematical tools.
- **Vadym V. Tiutiunyk** determined the area and extent of chemical damage in the braking area, analyzed the angular dimensions of actual chemical damage zones, and determined the depth of chemical damage and height of striking cloud rise for limiting degree of damage.

- **Elnur Shukurlu** determined the spill area of chemically hazardous substances, determined the height of spill on underlying surface, determined evaporation time (impact effect) of chemically hazardous substances, and determined quantity of spilt chemically dangerous substances in emergency stop area.

4. Conclusions

Every year there is an increase in the transportation of dangerous materials by road worldwide. It is accompanied by emergencies related to the depressurization of containers (tanks, containers, cylinders, etc.) in various circumstances (road accidents, natural cataclysms, terrorist acts, etc.). In such cases, dangerous chemicals can get into the environment and create significant risks to the population of surrounding areas and the environment.

Existing methods of effects evaluating chemical accidents cannot be used to solve the task due to their significant disadvantages (non-considering nature of the underlying surface; CHS absorption; parameters of spilling area of different CHS; use of mathematical apparatus obtained only empirically; use stationary chemically hazardous objects; they do not allow calculate risks of such emergency events for the population health).

New mathematical means of accident assessment were developed to transport hazardous substances in road transport. They, unlike existing ones, take into account the parameters of the car, speed of the driver's reaction, parameters of the depressurization of the tank, nature of the underlying surface, and parameters of construction in the area place of stay. The high accuracy of the proposed mathematical means is confirmed by comparing it with data from field measurements and results of calculations by other techniques.

Further implementation of the developed mathematical support in the form of software will be an effective tool for solving problems of preventive forecasting and prompt response to emergencies related to the entry of such substances into the environment while transporting them by road.

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References

[1] Fan T, Chiang W C and Russell R 2015 *Transportation Research Part D: Transport and Environment* **35** 104–115 URL https://doi.org/10.1016/j.trd.2014.11.009
[2] Carotenuto P, Giordani S, Ricciardelli S and Rismondo S 2007 *Computers & Operations Research* **34**(5) 1328–1350 Hazardous Materials Transportation URL https://doi.org/10.1016/j.cor.2005.06.004
[3] Brzozowska L 2016 *Transportation Research Part D: Transport and Environment* **43** 107–122 URL https://doi.org/10.1016/j.trd.2015.12.001
[4] Oggero A, Darbra R M, Muñoz M, Planas E and Casal J 2006 *Journal of Hazardous Materials* **133**(1) 1–7 URL https://doi.org/10.1016/j.jhazmat.2005.05.053
[5] Verter V and Kara B Y 2008 *Management Science* **54**(1) 29–40 URL https://doi.org/10.1287/mnsc.1070.0763
[6] Yang J, Li F, Zhou J, Zhang L, Huang L and Bi J 2010 *Journal of Hazardous Materials* **184**(1) 647–653 URL https://doi.org/10.1016/j.jhazmat.2010.08.085
[7] Helean J 2020 Parts of interstates closed in Birmingham after a truck carrying toxic chemicals overturned URL https://abc3340.com/news/local/overturned-18-wheeler-on-interstate-in-birmingham-contains-toxic-chemical
[8] 2019 Tanker truck crash, fuel spill shuts down New Jersey highway URL https://abc7ny.com/tanker-truck-new-jersey-marlboro-crash/5151216/

[9] Alp E 1995 *INFOR: Information Systems and Operational Research* **33**(1) 4–19 URL https://doi.org/10.1080/03155986.1995.11732263
[10] Van Raemdonck K, Macharis C and Mairesse O 2013 *Journal of Safety Research* **45** 55–63 URL https://doi.org/10.1016/j.jsr.2013.01.002
[11] Reniers G L L, Jongh K D, Gorrens B, Lauwers D, Leest M V and Witlox F 2010 *Transportation Research Part D: Transport and Environment* **15**(8) 489–496 URL https://doi.org/10.1016/j.trd.2010.07.001
[12] Bondžić J, Sremački M, Popov S, Mihajlović I, Vujić B and Petrović M 2021 *Journal of Environmental Management* **293** 112941 URL https://doi.org/10.1016/j.jenvman.2021.112941
[13] Popov O, Iatsyshyn A, Pecheny V, Kovach V and Kovalenko V 2023 Approaches to Assessing Consequences of Accidents During Transportation of Hazardous Substances by Road *Systems, Decision and Control in Energy IV: Volume II. Nuclear and Environmental Safety* ed Zaporozhets A and Popov O (Cham: Springer Nature Switzerland) pp 327–342 ISBN 978-3-031-22500-0 URL https://doi.org/10.1007/978-3-031-22500-0_22
[14] Popov O O, Kyrylenko Y O, Kameneva I P, Iatsyshyn A V, Iatsyshyn A V, Kovach V O, Artemchuk V O, Bliznyuk V N and Kiv A E 2022 *CTE Workshop Proceedings* **9** 306–322 URL https://doi.org/10.55056/cte.122
[15] Savchuk O 2014 *Forecasting and elimination of consequences in case of accidents (destruction) of mobile chemically hazardous objects* (St. Petersburg: St. Petersburg University of the State Fire Service of the Ministry of Emergency Situations of Russia)
[16] Aksenov A 2019 *Assessing the risk of chemical hazards while transporting hazardous chemically hazardous substances by road* (St. Petersburg: St. Petersburg University of the State Fire Service of the Ministry of Emergency Situations of Russia)
[17] Savchuk O 2013 *Chemical safety. System Analysis of Predicting Possible Consequences in Accidents (Destruction) of Chemically Hazardous Facilities* (Saarbrucken: LAMBERT Academic Publishing)
[18] Yatsyshyn T, Mykhailiuk Y, Liakh M, Mykhailiuk I, Savyk V and Dobrovolskyi I 2018 *Eastern-European Journal of Enterprise Technologies* **2**(10 (92)) 56–63 URL https://doi.org/10.15587/1729-4061.2018.126624
[19] Bolodyan I A *et al.* 2006 *Fire Risk Assessment Guide for Industrial Enterprises* (Moscow: FGU VNIIPO EMERCOM of Russia) URL https://meganorm.ru/Index2/1/4293830/4293830270.htm
[20] Andurand R 1987 Swift's assessment of the consequences of a relatively stable chlorine release *World Conference on Chemical Accidents. Rome, July 1987* (Edinburgh: CEP Consultants Ltd.) pp 337–340
[21] 2022 Vyznachennia neobkhidnoho povitroobminu prymishchen. Rekomendatsii do proektuvannia [Determination of the necessary air exchange of premises. Design recommendations] URL https://cutt.ly/Z2xBioI
[22] Writer S 2020 Northbound lanes on I-59/20 are still closed after an 18-wheeler carrying toxic chemicals overturned Thursday URL https://cutt.ly/p2xDwCg
[23] Ministry of Internal Affairs of Ukraine 2019 Methods for forecasting the consequences of spills (emissions) of hazardous chemicals during accidents at chemically hazardous facilities and transport URL https://zakon.rada.gov.ua/laws/show/z0440-20#top
[24] National Service Center for Environmental Publications 2007 ALOHA: user's manual URL https://nepis.epa.gov/Exe/ZyPDF.cgi/P1003UZB.PDF?Dockey=P1003UZB.PDF
[25] Berlyand M E *et al.* 1991 *Methodology for predicting the scale of contamination with potentially toxic substances in case of accidents (destruction) at chemically hazardous facilities and transport: Guiding document RD 52.04.253-90* (Leningrad: Gidrometeoizdat) URL https://files.stroyinf.ru/Data2/1/4293852/4293852297.pdf

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Application of environmental biomonitoring in environmental risk management of the fuel and energy complex

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Abstract. On the analysis basis of Ukraine fuel and energy complex priority problems, the key role of the introduction of international standards ISO 14000, ISO 9000 series and HSE policy to create conditions for the prevention of technological effects on environmental components and the formation of prerequisites for a safe environment, both for personnel and for the population of the surrounding territories, are determined. Deterioration of natural resources quality and ecosystems degradation and possible levels of natural environments pollution are used as parameters for environmental risk assessing in the conditions of the fuel and energy complex operation. The concept of environmental risk management in this field is presented. The biomonitoring uses to assess the factors influence of the industry enterprises is proposed. Biomonitoring of the territory around the Burshtyn thermal power plant is carried out, taxonomic characteristics of phytoobjects are given, and the indicative prospects of plants, their diversity and classes of permanence are evaluated. A literature analysis is carried out regarding the convenience, ease of use and phytoindicative suitability of plants under the conditions of the man-made environment complex impact. The highest species representativeness in *Asteraceae* family, represented by 17 species, *Fabaceae* and *Poaceae* – by 5 plant species, is established within the study area. The highest phytoindicative potential of *Cichorium intybus* L. and *Achillea millefolium* L. under the influence of Burshtyn thermal power station is revealed, which indicates the possibility of effective use of these plants as sensitive monitors of the fuel and energy complex enterprises ecological state.

1. Introduction

The facilities of the fuel and energy complex include thermal, hydro and nuclear power plants, the oil and gas and coal industry enterprises, oil and gas pipelines, transformer substations and power transmission lines. Electric power is one of the priority industries of Ukraine, which provides the country's needs in electric energy and exports a significant amount of electricity. Every year there is an increase in the consumption of oil, natural gas and electricity in the world due to constant urbanization and technogenesis. In particular, only in Ukraine for domestic needs by 2030, oil consumption is predicted to increase by 1.5 times, coal – by 2 times, and electricity – by 2.2 times.

Each element of the fuel and energy complex belongs to the category of environmentally hazardous and has a negative impact on the environment, including a direct or indirect impact on the health of personnel. These objects are a source of chemical and physical pollution of local, regional and global levels of air, soil, surface and underground water, the cause of climate change – the greenhouse effect, acid rain, smog, global warming, as well as the reduction of biological diversity. The reasons for the increase in the chemical and physical pollution levels during the activities of oil and gas industry and energy facilities are outdated equipment and technologies for extraction, transportation, processing and use of natural fuel resources. In addition to a number of chemicals toxic to the environment, such as heavy metals, petroleum products, acid oxides, the level of electromagnetic, noise and vibration pollution in the environment increases during the operation of fuel and energy complex facilities. In this respect, power plants and power lines pose a particular danger, the physical pollution from which in most cases significantly exceeds the permissible levels [1–3]. Therefore, establishing an environmental management system based on modern standards ISO 9000, ISO 14000, Health, Safety, Environment policies (HSE) with the use of effective methods of monitoring the ecological state of the environment under the influence of complex pollution from energy and fuel industry facilities is an urgent task ensuring environmental safety of the industry.

2. Literature review and problem statement

The implementation of the ecosystem approach in sectoral policy and improvement of the of integrated environmental management system is one of the tasks of the State Environmental Policy Strategy of Ukraine for the period up to 2030. Thus, one of the principles of this policy is the prevention of emergencies of a natural and man-made environment, which involves the analysis and forecasting of environmental risks, which are based on the results of a strategic environmental assessment, the environmental impact assessment, as well as comprehensive monitoring of the natural environmental state [4–6]. By ratifying the Protocol on Accession to the Treaty on the Energy Community Establishment, Ukraine undertook to implement the regulatory framework of the European Community on energy, environmental protection, competition policy and renewable energy sources [7, 8].

One of the essential steps in gradually achieving compliance with EU technical regulations and standardization and metrology systems was the ratification by Ukraine of the Association Agreement between Ukraine, on the one hand, and the European Union, the European Atomic Energy Community and their member states, on the other hand [4, 9]. According to this Agreement, our country undertakes to adhere to the principles and practices set forth in current EU decisions and regulations. Also, Ukraine undertook the gradual implementation of European standards (EN) as national standards. At the same time, conflicting national standards, in particular the application of interstate standards (GOST/GOST) developed before 1992, are canceled [10].

Thus, the enterprises policy should be based on the principle of preventing the occurrence of dangerous ecological consequences for the environment, personnel and the population of the surrounding territories, while one of the main tools is the monitoring and assessment of the existing environmental state.

There are a number of conceptual approaches for an environmentally safe production process, which are used at the facilities of the fuel and energy complex [8, 11].

The specified principles require appropriate tools that will allow making environmentally safe management decisions at the early stages of designing the planned activity. The task of obtaining a group quantitative expert assessment taking into account the coefficients of the estimated indicators relative importance of the planned activity impact on the environment is currently solved by the criterion-expert weighting methods, which form the basis of the information support of life cycle assessment (LCA) methodology, which is widely used in the environmental design practice in Western Europe and America countries [4]. The theoretical foundations of this approach are approved in international standards of the ISO 14040-14049 series "Life cycle analysis methodology" [8].

An important tool for managing environmental safety, preventing health impacts and creating a safe production environment is the policy "Health, Safety, Environment (HSE)" – these are separate issues, each with its own technology, but they are often combined into the same functional groups in fuel and energy companies. The main principles of this policy at fuel and energy facilities are [4, 12]:

- to aim at creating a safe, encouraging working environment;
- to warn about danger and take measures to prevent it;
- to provide education and training in order to ensure compliance with laws and regulations related to occupational H&S and to maintain and develop H&S workplaces and management systems;
- to lead efforts to address environmental issues on a global scale and for local communities by recognizing environmental measures as a pressing issue towards the creation of green and sustainable energy systems.

The creation of a favorable production environment from the point of environmental protection view and safe working conditions is based on the environmental components monitoring and their changes under the influence of man-made factors. Among the environmental monitoring methods biological monitoring deserves attention, and in particular, one of the most promising methods is phytomonitoring – the use of plant organisms that exist in a certain territory as a population and respond to ecological changes in the environment with a number of appropriate reactions [13]. Plant organisms are widely known for their phytoremedial and phytoindicative properties, and their ability to exhibit wide ecological plasticity in accordance with the genetically programmed capabilities of the reaction norm [14, 15]. A large number of publications are devoted to the study of indicative parameters of the vital state of plants in conditions of anthropogenic pollution [16–18].

However, there are relatively few works dealing with the role of herbaceous phytocenoses as objects of biological monitoring of the territories around the enterprises of the fuel and energy complex.

3. Objectives and methods

During the activity of the fuel and energy complex enterprises, in addition to the toxic substances influence, there is the electromagnetic, noise and vibration pollution influence, which creates conditions for disturbing the balance in natural systems and the human body. Creating conditions for its prevention and researching possible consequences on the environment is an urgent scientific task. The main tasks of this article are:

- to establish the environmental policy principles of the fuel and energy complex, which should create conditions for preventing the consequences of its influence;
- to propose the concept of environmental risk management for the fuel and energy complex objects;
- to analyze literature data on the possible of chemical and physical pollution impact of fuel and energy complex objects on the vital plants state, as well as on animal biodiversity and human health;
- to conduct a taxonomic and biomorphic plants characterization under the pollution conditions from the Burshtyn thermal power station;

- to evaluate the types of vegetation cover diversity, its vital state, distribution in the territory around one of the largest industrial enterprises of the fuel and energy complex of Ukraine – the Burshtyn thermal power plant;
- to identify the most promising plants-indicators of the territories ecological state around the Burshtyn Thermal Power Station with the aim of introducing them into the system of ecological monitoring of territories located near powerful energy facilities.

In the course of environmental management research, the analysis, deduction and system-structural methods are used. Detection of environmental impacts of the fuel and energy complex is based on the life cycle assessment method. The establishment of monitoring plots in the territory around the Burshtyn power station is carried out according to the author's methodology [19]. The establishment of life forms is based on biomorphological classification, the species composition of the phytocenoses of the experimental area is recorded using the Plant Snap mobile program, the phytocenotic diversity, the permanence class of each species is established according to the generally accepted methodology [19].

4. Research results

4.1. Environmental risk management of the fuel and energy complex facilities

The current priorities of the world community demand comprehensive control and reduction of environmental pollution. Effective management of environmental safety requires constant monitoring to identify the "weaknesses" of the existing management system.

At this stage, the system of environmental management in Ukraine is at the stage of formation, this also applies to the fuel and energy industry. The lack of an effective environmental policy of the fuel and energy complex of Ukraine in previous decades caused the accumulation of problems, the solution of which requires the regulatory documents appropriate base creation and a scheme for their implementation. At this stage, the pollution created by the fuel and energy complex increases the level of environmental and social risk in the spatial context.

According to the data of the Department of Labor Protection, Environmental and Industrial Policy of Naftogaz of Ukraine, intensive work is currently underway in the direction of integration into the European Energy Community. Among the important tasks is the implementation of EU Directives, international and European standards, including environmental protection management issues. The specified activity will minimize environmental risks during production activities and increase the level of environmental safety. Such positive trends will provide an opportunity to improve the company's international image and increase investment attraction. In 2018, the company received ISO 14001:2015, OHSAS 18001:2010 and ISO 50001 certificates from the authoritative international certification body TÜV SÜD Management Service GmbH, and in 2017, it passed a third-party surveillance audit for compliance with ISO 9001:2015 requirements. At present, Naftogaz has implemented the "VISION ZERO" vision – the HSE (Health, Safety and Environment) vision, according to which injuries, deaths, accidents and other negative consequences from operational activities are unacceptable [20, 21]. The spheres of influence considered within the framework of the HSE policy are of primary importance for the fuel and energy industry, and compliance with the guiding principles of safety and environmental protection is mandatory and dictated by the internal policy of most corporations. The implementation of the HSE policy makes it possible to define the principles by which operations are carried out and risks are controlled throughout the industrial cycle. Figure 1 shows the process of risk assessment and management in the HSE system.

The basis for building an environmental management system in the fuel and energy sector is the ISO 14000 series international standards and the corresponding national standards [8].

The trends of the modern environmental policy of the fuel and energy complex of Ukraine allow us to conclude that specialized companies strive to improve the environmental management

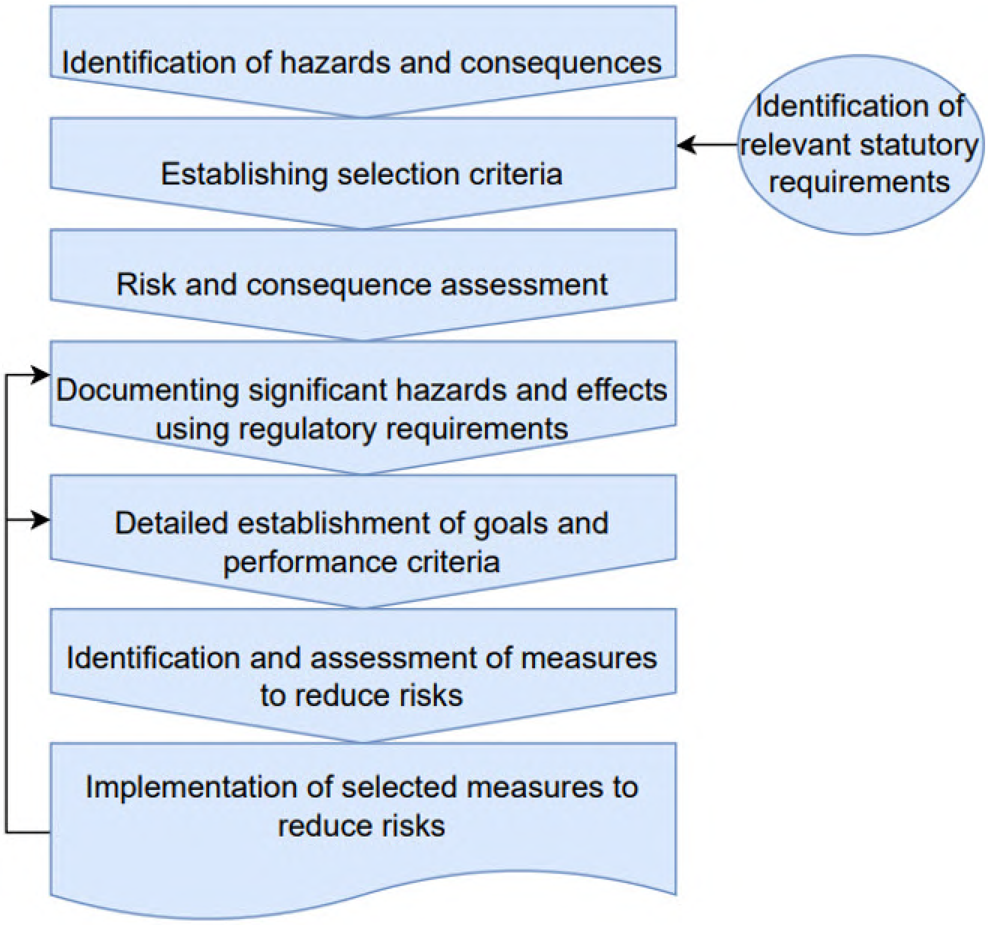

Figure 1. Risk assessment and management process [20].

system in order to meet the requirements of the EU and strengthen their stable positions on the European market. Solving the tasks is based on the comprehensive implementation of the environmental management system, the basis of which is laid in the international quality standards of the ISO 14000 series [7]. The ISO 9000 series international standards provide ideas for a systematic approach to management, decision-making based on factual material, and continuous improvement of the organization as a whole [10]. The specified principles require appropriate tools that will allow making ecologically safe management decisions at the early stages of man-made activities designing. Therefore, there is a need to use effective tools for assessing and monitoring the existing impacts consequences on the environment for the possibility of improving the eco-efficiency indicators of fuel and energy enterprises.

There are a number of methods for determining the environmental safety level based on environmental risk assessment [22, 23].

This approach is considered one of the promising tools for making managerial decisions. Along with the environmental safety assessment of naturall components, it is appropriate to assess the level of environmental safety based on biomonitoring.

One of the environmental risk definitions is the probability of adverse consequences for the environment, any changes in natural objects and factors, occurrence of extraordinary events in a certain period of time, expressed by quantitative parameters. Such parameters can be the following values:

- possible natural indicators of damage, that is, the number of victims and destroyed objects, the amount of the lost harvest;
- the possible dimensions of the quality deterioration of natural resources, degradation of ecosystems;
- the possible level of natural environments pollution.

Environmental risk assessment, which is predictive in nature, is carried out by three main methods:

- the method of analogy, i.e. comparison with other similar objects, and the comparison is made according to the same parameters;
- according to statistical data based on similar phenomena that have already happened;
- in a theoretical way, that is maintained by mathematical modeling.

In order to determine the optimal method of environmental risk assessment, it is necessary to take into account the origin of negative impact factors (phenomena), processes in the ecological system that suffered damage, the final state of the ecosystem (consequences of the negative factor of the environment and public health components). Depending on the level, there are features of environmental risk analysis (table 1).

The above indicates the need for an integrated approach to ecological and economic risk assessment at the cross-border level. The risk assessment methodology in the spatial context should be based on the compliance of its principles with European directives and be oriented

Table 1. Peculiarities of environmental risk analysis at the micro and macro levels [24].

Components of the analytical procedure	**Levels of environmental risk analysis objects research**	
	Micro level	**Macro level**
Aim	Assessment of direct damage from man-made phenomena.	Consequences determination of environmental damage for the natural territorial complex components.
Model of the analyzed system	Deterministic matching functions.	The function of probabilistic characteristics.
General appearance of the model	*Risk=M(x)*, where *M(x)* – mathematical expectation of a negative phenomenon.	$Risk = P(x) \cdot M(x)$, where *P(x)* – the probability of a negative impact on the natural-territorial complex components.
Quantitative analysis	$Risk = \frac{1}{CL_{50}} \sum_{i=1}^{n} \frac{C_i}{MPC_i}$, where CL_{50} – the lethal concentration of the toxicant in the waste as a criterion of toxicity, C_i – the content of toxic substances in the components of the environment, MPC – maximum permissible concentration.	$Risk = -P_i \cdot \ln(P_i)$, where P_i – the probability of a negative impact on the i-th component of the environment: $P_i = \frac{1}{\sqrt{2\pi} \cdot \sigma_{min} \cdot K} \cdot \exp\left[-\frac{x}{2 \cdot \sigma_{min}^2}\right]$, where K – hazard class value, σ_{min} – normalized indicator.

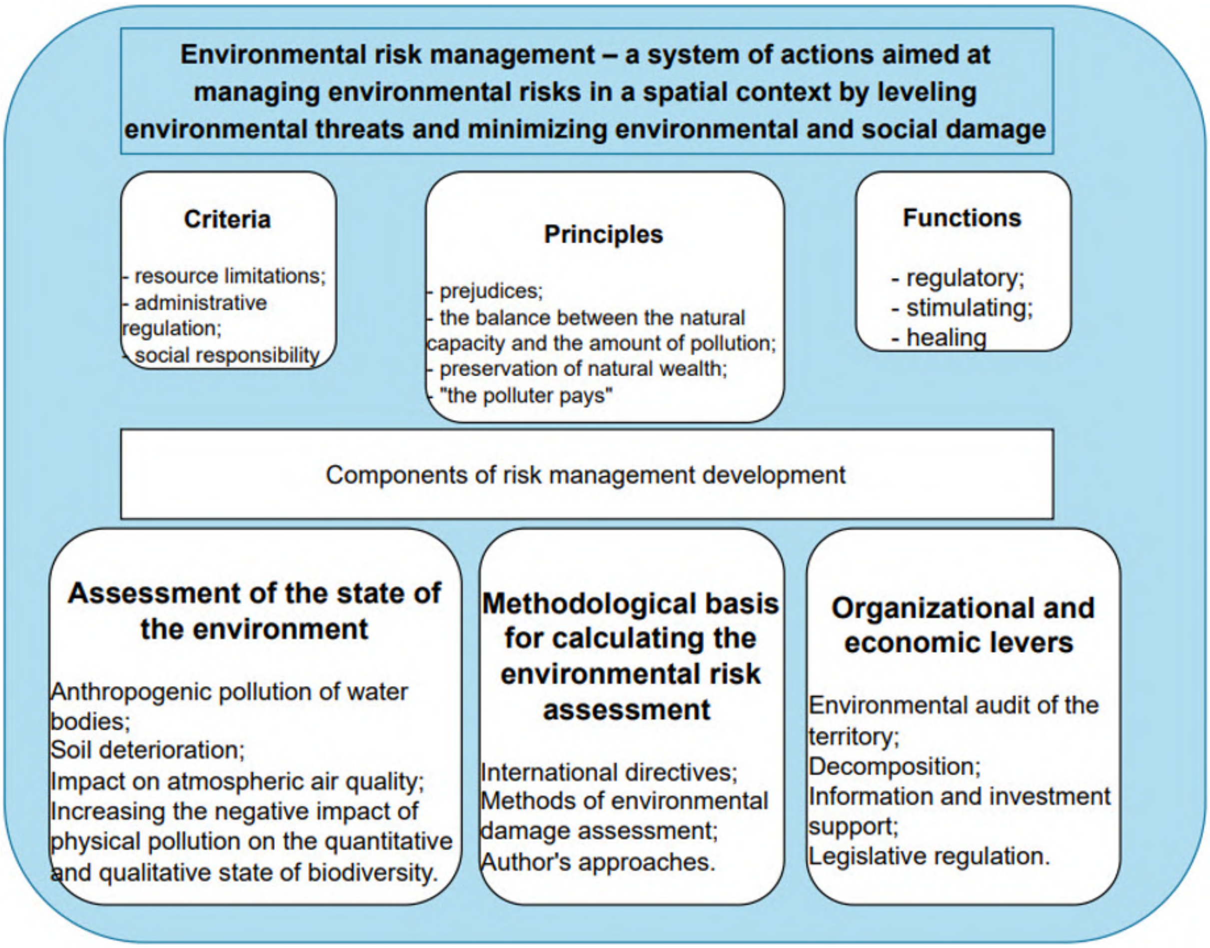

Figure 2. Risk management of fuel and energy complex facilities.

towards the transformation of national environmental protection legislation. In figure 2 presents the proposed concept of risk management of the fuel and energy complex [25].

An important role in the risk management implementation belongs to the choice of implementation methods of the stages indicated in figure 2. In this work, attention is paid to the environment quality assessment under the influence of complex chemical and physical pollution from the Burshtyn thermal power station on the vital state of plant communities. The diversity types, constancy and bioindicative potential of plants that exist under the influence of an industrial enterprise are analyzed.

4.2. Biomonitoring in conditions of complex environmental pollution by the fuel and energy enterprises

The research was carried out under the influence of the Burshtyn thermal power station, located in the Ivano-Frankivsk region at the intersection of power lines connecting Ukraine with Hungary, Romania and Slovakia.

Within a radius of up to 1 km from the source of pollution, seven monitoring sites with an area of 25 m^2 have been laid. The species composition of phytocenoses, abundance, family membership and life forms are analyzed within each site. A biomorphological analysis of the flora is carried out by assigning each type of plant to a specific biomorph and expressing the number of species of each biomorph in percentages. A taxonomic characterization of plants is carried out at each monitoring site and the phytocoenotic diversity of plants is calculated. Phytocoenotic diversity is determined as a percentage, taking as 100% the diversity of plants in the monitoring area with the largest number of plant species. Accordingly, phytocoenotic diversity is calculated in all other points, having the total species number of plants of these points.

To identify dominant and diagnostic species in the monitoring system, plant lists are compiled and the number of monitoring points where each plant species is present is analyzed. If the species is present in all monitoring points, its persistence coefficient is taken as 100%, if in some of the points, then the persistence coefficient is calculated proportionally. For example, if 25 points are entered in the table, and the species is present in 10 points, then the coefficient of constancy is equal to: $C = 10 \cdot 100/25 = 40\%$, if in 5 descriptions – 20%, etc.

All types of plants are divided into three groups depending on the constancy coefficient value. With values of the coefficient constancy over 60%, the species belong to the group of high constancy; with values of the coefficient constancy 20-60% – medium stability; with values of the coefficient constancy less than 20% – low constancy. The constancy class of each species is determined according to the scheme:

I class – less than 20%;
II class – 21-40%;
III class – 41-60%;
IV class – 61-80%;
V class – 81-100%.

The main environmental pollutants entering the atmosphere as a result of the power plant operation include acid oxides, which cause acid rain and cause tissue necrosis in plants and their subsequent death. In addition, a change in the natural value of pH in soil ecosystems inhibits the growth and development of plant seeds and causes the death of invertebrates [26,27]. Heavy metals present in industrial Burshtyn thermal power station emissions led to the biosynthetic processes blocking in plant tissues, inhibit cell division, photosynthesis and cause premature aging of plants.

According to the literature, low-frequency electromagnetic radiation leads to a decrease in the biomass of earthworms, blocking the mitochondrial activity, gene expression disruption and lipid and protein metabolism changes in Caenorhabditis elegans [28, 29]. Electromagnetic radiation causes changes at the level of informational relations between individuals in insect populations, disrupts physiological indicators, metabolism, growth and development, and leads to the appearance of mutations. Electromagnetic influence manifests itself in the disruption of intraspecific communications in birds, fish and reptiles [23, 30–32].

The consequences of short-term exposure to electromagnetic radiation on the human body include headache, general weakness, increased fatigue, sleep disturbances, irritability, and slowing of motor and speech reactions [33]. Long-term electromagnetic influence leads to a decrease in pulse frequency, a decrease in blood pressure, changes in blood composition, intensification of cell proliferation, reduced work capacity, changes in the activity of the internal secretion glands, circulatory, digestive, cardiovascular and nervous systems disorders, hair loss, fragility nails, skin diseases [31, 34]. It is known that electromagnetic radiation inhibits the growth and development processes of plants, causes changes in the shape and size of flowers, leaves, stems, the appearance of extra petals, and a decrease in plants dry weight [26,27,35]. The phytocoenotic diversity of the territory is an indicator of the ecological system environmental state, therefore, the study of the plant community's species composition makes it possible to identify the most promising species in terms of phytoindication [36, 37].

Under the influence of Burshtyn thermal power station 45 species of herbaceous plants and 1 tree species belonging to 18 families are recorded in the monitoring areas (table 2). The dominant family is Asteraceae represented by 17 species, *Fabaceae* and *Poaceae* – by 5 species each. The family *Hypericaceae* is represented by three species of plants, *Rosaceae*, *Plantaginaceae* and *Apiaceae* – by two species, the rest of the families in the monitoring areas have one representative of the plant species each.

Table 2. Species diversity of phytocenoses at monitoring points of the complex impact of the Burshtyn thermal power station.

Monitoring sites	Coordinates	Plant species
1	49°10'36.35"N 24°41'74.55"E	*Artemisia vulgaris* L., *Centaurea jacea* L., *Achillea millefolium* L., *Hieracium umbellatum* L., *Bellis annua* L., *Cichorium intybus* L., *Prunus cerasifera* Ehrh., *Crataegus monogyna* Jacg., *Hypericum perforatum* L., *Lotus corniculatus* L., *Molinia caerulea* (L.) Moench., *Daucus carota* L.
2	49°10'27.68"N 29°41'06.39"E	*Medicago sativa* L., *Trifolium repens* L., *Lotus corniculatus* L., *Centaurea jacea* L., *Achillea millefolium* L., *Tanacetum vulgare* L., *Erigeron annuus* (L.) Desf., *Cichorium intybus* L., *Hypericum perforatum* L., *Calamagrostis epigejos* (L.) Roth., *Agrostis capillaris* L., *Molinia caerulea* (L.) Moench., *Agrimonia eupatoria* L., *Pastinaca sativa* L.
3	49°12'02.38"N 24°40'02.99"E	*Delphinium consolida* L., *Erigeron annuus* (L.) Desf., *Sonchus arvensis* L., *Erigeron canadensis* L., *Arctium tomentosum* Mill., *Cichorium intybus* L., *Vicia villosa* Roth., *Trifolium pratense* L., *Lotus corniculatus* L., *Medicago sativa* L., *Persicaria lapathifolia* L., *Lamium album* L., *Daucus carota* L., *Pastinaca sativa* L., *Papaver rhoeas* L.
4	49°12'02.34"N 24°39'66.22"E	*Artemisia vulgaris* L., *Cirsium arvense* (L) Scop., *Centaurea jacea* L., *Achillea millefolium* L., *Tanacetum vulgare* L., *Crepis capillaris* (L.) Wallr., *Cichorium intybus* L., *Erigeron annuus* (L.) Desf., *Oenothera biennis* L., *Convolvulus arvensis* L., *Vicia villosa* Roth., *Hypericum perforatum* L., *Calamagrostis epigejos* (L.) Roth., *Linaria vulgaris* Mill., *Daucus carota* L., *Silene latifolia* Poir.
5	49°12'13.6"N 24°40'01.0"E	*Lactuca serriola* L., *Achillea millefolium* L., *Solidago canadensis* L., *Hieracium umbellatum* L., *Tussilago farfara* L., *Artemisia vulgaris* L., *Cichorium intybus* L., *Anthemis arvensis* L., *Salix purpurea* L., *Rorippa sylvestris* (L.) Besser., *Trifolium pratense* L., *Daucus carota* L., *Puccinellia distans* L., *Silene latifolia* Poir., *Deschampsia cespitosa* (L.) P. Beauv.
6	49°15'30.3"N 24°37'59.3"E	*Cirsium arvense* (L) Scop., *Achillea millefolium* L., *Lactuca serriola* L., *Arctium tomentosum* Mill., *Artemisia vulgaris* L., *Cichorium intybus* L., *Verbena officinalis* L., *Trifolium pratense* L., *Lotus corniculatus* L., *Medicago sativa* L., *Daucus carota* L., *Plantago lanceolata* L., *Dipsacus fullonum* L.
7	49°12'09.59"N 24°40'66.00"E	*Verbena officinalis* L., *Achillea millefolium* L., *Arctium tomentosum* Mill., *Artemisia vulgaris* L., *Cichorium intybus* L., *Trifolium pratense* L., *Lotus corniculatus* L., *Medicago sativa* L., *Daucus carota* L., *Plantago lanceolata* L.

In the conditions of the monitoring sites, a relatively uniform diversity of plant cover is noted with the lowest phytocenotic diversity – 63% (table 3). The number of plant species varies between 10-16, the number of families – between 5-9.

Phytocoenotic diversity under Burshtyn thermal power station influence is represented by all classes of constancy (table 4).

The V class of permanence includes two species of *Achillea millefolium* L. and *Cichorium intybus* L., which are expedient to use in phytomonitoring of complex pollution areas from the fuel and energy complex facilities (figure 3, figure 4).

Table 3. Taxonomic characteristics of phytocenoses at monitoring points of the Burshtyn thermal power station complex impact.

Monitoring site	Number of plant families	Number of species	Phytocoenotic diversity, %
1	6	12	75
2	6	14	88
3	7	15	94
4	9	16	100
5	8	15	94
6	6	13	81
7	5	10	63

Table 4. Persistence of plant species in the phytocenoses composition under the conditions of Burshtyn thermal power station complex impact.

Species	Constancy, %	Constancy class
Cichorium intybus L.	100	V
Achillea millefolium L.	86	V
Artemisia vulgaris L., *Lotus corniculatus* L., *Daucus carota* L.	71	IV
Medicago sativa L., *Trifolium pratense* L.	57	III
Centaurea jacea L., *Erigeron annuus* (L.) Desf., *Arctium tomentosum* Mill., *Hypericum perforatum* L.	43	III
Hieracium umbellatum L., *Tanacetum vulgare* L., *Cirsium arvense* (L.) Scop., *Vicia villosa* Roth., *Molinia caerulea* (L.) Moench., *Calamagrostis epigejos* (L.) Roth., *Pastinaca sativa* L.	29	II
Bellis annua L., *Sonchus arvensis* L., *Erigeron canadensis* L., *Crepis capillaris* (L.) Wallr., *Lactuca serriola* L., *Solidago canadensis* L., *Tussilago farfara* L., *Anthemis arvensis* L., *Agrimonia eupatoria* L., *Prunus cerasifera* Ehrh., *Crataegus monogyna* Jacg., *Trifolium repens* L., *Agrostis capillaris* L., *Puccinellia distans* L., *Deschampsia cespitosa* (L.) P. Beauv., *Delphinium consolida* L., *Persicaria lapathifolia* L., *Lamium album* L., *Papaver rhoeas* L., *Oenothera biennis* L., *Convolvulus arvensis* L., *Plantago lanceolata* L., *Linaria vulgaris* Mill., *Silene latifolia* Poir., *Salix purpurea* L., *Rorippa sylvestris* (L.) Besser., *Verbena officinalis* L., *Dipsacus fullonum* L.	14	I

Figure 3. *Achillea millefolium* L. under Burshtyn thermal power station influence.

Figure 4. *Cichorium intybus* L. under Burshtyn thermal power station influence.

The species *Artemisia vulgaris* L., *Lotus corniculatus* L., *Daucus carota* L. have medium bioindicative potential, and the species *Medicago sativa* L., *Trifolium pratense* L., *Centaurea jacea* L., *Erigeron annuus* (L.) Desf., *Arctium tomentosum* Mill., *Hypericum perforatum* L. have a low monitoring capacity. Half of the species belong to the I class of permanence, so they cannot be used for bioindicative purposes.

5. Discussion

The implementation of the ISO 14000, ISO 9000 series standards and the introduction of the HSE policy at the enterprises of the fuel and energy complex involves the constant improvement of processes and technologies to reduce the impact on the environment and prevent the occurrence of man-made impacts on the environment. In this aspect, an extremely important role is played by improving the qualifications of personnel regarding safe work within specialized enterprises.

Among the 45 species of herbaceous plants *Achillea millefolium* L. and *Cichorium intybus* L. have the highest representativeness on the monitoring sites, which indicates their phytoindicative potential and the possibility of being used as ecological state biological monitors of the territories around industrial and energy enterprises. In the absence of the specified species in the experimental area *Artemisia vulgaris* L., *Lotus corniculatus* L., *Daucus carota* L. can also be used for phytoindication. The remaining species around the Burshtyn power station are characterized by low prevalence and are not appropriate as phytoindicators of the specified industrial facility ecological state.

6. Conclusions

1. The concept of environmental risk management in this field is presented. Among the environmental risk assessment parameters in the conditions of the fuel and energy complex, the deterioration of the natural resources quality and the ecosystems degradation and the pollution possible levels of natural environments are highlighted.
2. It is proposed to use biomonitoring to assess the factors influence of this complex enterprises on the environment components. The bioindicative potential of *Achillea millefolium* L. and *Cichorium intybus* L. under the influence of pollution from the Burshtyn thermal power station is established. It is proposed to use species as biological monitors of the territories ecological state affected by the fuel and energy complex enterprises.
3. It was established that only 10% of all phytocenoses types that exist under the influence of

the industrial enterprise show high resistance to pollution under the operation conditions of the Burshtyn thermal power station. The significant diversity of plant species in the area of the enterprise influence indicates the natural potential of this ecosystem vegetation for self-preservation, however, the small representativeness of plant species indicates a significantly weakened reproductive potential in stressful existence conditions. In general, in unfavorable growth conditions, plants direct their energy resources to self-maintenance, and the processes of self-reproduction in these conditions of existence are suppressed.

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References
[1] 2006 DSTU ISO 14041:2004. Ekolohycheskoe upravlenye otsenka zhyznennoho tsykla. Opredelenye tsely y sfery prymenenyia y analyzyrovanye ynventaryzatsyy (ISO 14041:1998, IDT) URL http://online.budstandart.com/ru/catalog/doc-page?id_doc=51326
[2] 2006 DSTU ISO/TR 14049:2004. Ekolohycheskoe upravlenye. Otsenyvanye zhyznennoho tsykla. Prymery prymenenyia iso 14041 dlia opredelenyia tsely y sfery prymenenyia y analyz ynventaryzatsyy (ISO/TR 14049:2000, IDT) URL http://online.budstandart.com/ru/catalog/doc-page?id_doc=51327
[3] Lysychenko G, Weber R, Kovach V, Gertsiuk M, Watson A and Krasnova I 2015 *Environmental Science and Pollution Research* **22**(19) 14391–14404 ISSN 1614-7499 URL https://doi.org/10.1007/s11356-015-5184-1
[4] Bakulin E M, Yavorsky M M, Svitlitsky V M, Kryzhanivskyy Y I and Karpash O M 2007 *Naftohazova enerhetyka* (1) 5–11 URL http://elar.nung.edu.ua/handle/123456789/1289
[5] Verkhovna Rada of Ukraine 2019 Law of Ukraine "About the Basic principles (strategy) of the state environmental policy of Ukraine for the period up to 2030" URL https://zakon.rada.gov.ua/laws/show/2697-19#Text
[6] Popov O O, Kyrylenko Y O, Kameneva I P, Iatsyshyn A V, Iatsyshyn A V, Kovach V O, Artemchuk V O, Bliznyuk V N and Kiv A E 2022 *CTE Workshop Proceedings* **9** 306–322 URL https://doi.org/10.55056/cte.122
[7] Berzina S V 2009 *Environmental management systems Reference guide for the implementation of international standards series ISO 14000* (Kyiv: Aiva Plus Ltd) URL https://podil.kyivcity.gov.ua/files/2015/11/27/SysEco.pdf
[8] Berzina S V, Buzan H S, Vakarash V M, Kniazkova T V, Vorfolomeiev A V, Haidaienko Y V, Kravchenko B M, Tkach O V, Chaikovskyi O A, Khokhotva O P, Tsybka M M and Shylovych I L 2017 *Environmental management systems: current trends and international standards* (Kyiv: Institute of Environmental Management and Sustainable Environmental Management) URL https://www.ecolabel.org.ua/images/page/dovidnyk_ssp.pdf
[9] Verkhovna Rada of Ukraine 2014 Association Agreement between Ukraine, on the one hand, and the European Union, the European Atomic Energy Community and their member states, on the other hand URL https://zakon.rada.gov.ua/laws/show/984_011#Text
[10] 2014 DSTU ISO 14040:2013 Ekolohichne upravlinnia. Otsiniuvannia zhyttievoho tsyklu. Pryntsypy ta struktura (ISO 14040:2006, IDT) URL http://online.budstandart.com/ua/catalog/doc-page?id_doc=70997
[11] Yatsyshyn T M 2019 *Prospecting and Development of Oil and Gas Fields* **3**(72) 83–92 URL https://doi.org/10.31471/1993-9973-2019-3(72)-83-92
[12] Kovalko O M, Khomyk P M, Andriyevs'kyy A V and Trusova M V 2016 *Naftohazova haluz' Ukrayiny* **2** 5–8 URL http://elar.nung.edu.ua/handle/123456789/3844
[13] Capuana M 2020 *iForest - Biogeosciences and Forestry* (2) 139–151 URL https://doi.org/10.3832/ifor3242-013
[14] Treesubsuntorn C, Setiawan G D, Permana B H, Citra Y, Krobthong S, Yingchutrakul Y, Siswanto D and Thiravetyan P 2021 *Science of The Total Environment* **794** 148779 URL https://doi.org/10.1016/j.scitotenv.2021.148779
[15] Kováts N, Hubai K, Diósi D, Sainnokhoi T A, Hoffer A, Ádám Tóth and Teke G 2021 *Ecological Indicators* **124** 107428 URL https://doi.org/10.1016/j.ecolind.2021.107428

[16] Khalid N, Masood A, Noman A, Aqeel M and Qasim M 2019 *Chemosphere* **235** 832–841 URL `https://doi.org/10.1016/j.chemosphere.2019.06.143`

[17] Pietrelli L, Menegoni P and Papetti P 2022 *Water, Air, & Soil Pollution* **233**(4) URL `https://doi.org/10.1007/s11270-022-05577-x`

[18] Anand P, Mina U, Khare M, Kumar P and Kota S H 2022 *Atmospheric Pollution Research* **13**(8) 101508 URL `https://doi.org/10.1016/j.apr.2022.101508`

[19] Adamenko Y O, Arkhipova L M, Hlibovytska N I, Mandryk O M, Orfanova M M and Shtogrin M V 2022 *Impact of electricity on the environment: laboratory workshop* (Ivano-Frankivsk: IFNTUNG)

[20] 2015 Environmental Issues | HSE – Basic Concepts URL `https://www.oil-gasportal.com/environmental-issues/hse-basic-concepts`

[21] Kiminami Y 2022 HSE (health, safety, environment) Policy URL `https://www.renovainc.com/en/sustainability/hse`

[22] Obykhod H O and Omel'yanenko T L 2012 *Efektyvna ekonomika* **10** URL `http://www.economy.nayka.com.ua/?op=1&z=1429`

[23] Rybalova O V, Belan S V and Varyvoda Y E 2010 *Problemy nadzvychaynykh sytuatsiy* **12** 132–142 URL `http://edu-mns.org.ua/nmc/94/pns12.pdf`

[24] Kozulya T V and Emelyanova D I 2015 *Problemy informatsiynykh tekhnolohiy* **17** 138–144 URL `http://nbuv.gov.ua/UJRN/Pit_2015_1_24`

[25] Karpenko O O and Kostecka K O 2009 *Ekonomichni innovatsiyi* **35**(2) 372–381

[26] Diprose M F, Benson F A and Willis A J 1984 *The Botanical Review* **50**(2) 171–223 URL `https://doi.org/10.1007/BF02861092`

[27] Farghaly Y A, Hemeida F A A and Salah S 2019 *PLOS ONE* **14**(7) 1–20 URL `https://doi.org/10.1371/journal.pone.0219373`

[28] Ogunjo S T, Williams A O, Egbuonu F O and Adedayo K D 2012 *Environtropica* **9&10** 37–44 URL `https://www.researchgate.net/publication/256359068`

[29] Sun Y, Huang X, Wang Y, Shi Z, Liao Y and Cai P 2019 *Ecotoxicology and Environmental Safety* **170** 611–619 URL `https://doi.org/10.1016/j.ecoenv.2018.11.137`

[30] Ortega C 2012 *Ornithological Monographs* **74** 6–22 URL `https://doi.org/10.1525/om.2012.74.1.6`

[31] Swaddle J P, Francis C D, Barber J R, Cooper C B, Kyba C C M, Dominoni D M, Shannon G, Aschehoug E, Goodwin S E, Kawahara A Y, Luther D, Spoelstra K, Voss M and Longcore T 2015 *Trends in Ecology & Evolution* **30**(9) 550–560 URL `https://doi.org/10.1016/j.tree.2015.06.009`

[32] Slabbekoorn H and Ripmeester E A P 2008 *Molecular Ecology* **17**(1) 72–83 URL `https://doi.org/10.1111/j.1365-294X.2007.03487.x`

[33] Farooqi Z U R, Sabir M, Latif J, Aslam Z, Ahmad H R, Ahmad I, Imran M and Ilić P 2020 *Environmental Science and Pollution Research* **27**(3) 2819–2828 ISSN 1614-7499 URL `https://doi.org/10.1007/s11356-019-07105-7`

[34] Mesfin K, Hasen A S and Birhanu M 2018 *International Journal of Environmental Sciences & Natural Resources* **8**(2) 61–65 URL `https://doi.org/10.19080/IJESNR.2018.08.5`

[35] Maleki K and Hosseini S M 2011 *Annals of Environmental Science* **5** URL `https://openjournals.neu.edu/aes/journal/article/view/v5art3`

[36] Yatsyshyn T, Glibovytska N, Skitsa L, Liakh M and Kachala S 2020 Investigation of Biotechnogenic System Formed by Long-Term Impact of Oil Extraction Objects *Systems, Decision and Control in Energy I* ed Babak V, Isaienko V and Zaporozhets A (Cham: Springer International Publishing) pp 165–177 ISBN 978-3-030-48583-2 URL `https://doi.org/10.1007/978-3-030-48583-2_11`

[37] Yatsyshyn T M, Lyakh M M, Orfanova M M, Glibovytska N I, Gavryliv S Y and Lyakh V D M 2022 *IOP Conference Series: Earth and Environmental Science* **1049**(1) 012017 URL `https://doi.org/10.1088/1755-1315/1049/1/012017`

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Abstract. The general aim of this research is to analyze spatial-temporal changes of air quality, which are the consequences of the military invasion of the Russian on the territory of Ukraine based on open remote sensing data, geoinformation and cloud technologies. The density of NO_2, SO_2, CO and HCHO as well as the density of O_3 and the absorbing aerosol index (AAI) extracted from the Sentinel-5P satellite using Google Earth Engine (GEE) showed reduced emission of primary air pollutants and a high level of atmospheric restoration compared to 2021, the year before the war. At the same time values of the AAI increased significantly, indicating the presence of smoke and dust in the air. Obtained results showed one more aspect of the drastic effect of the war on the economic and social processes and environmental conditions. The consequences of this ecological effect can have a long-term negative impact on the health of populations.

1. Introduction

The full-scale war unleashed by Russia on Ukraine's territory caused irreparable loss of population, damage to the infrastructure and destruction of the economy, but also caused a significant deterioration of the environment and the formation of significant ecological problems. Thus, as preliminary estimated [1], 900 protected natural territories of Ukraine have been affected and more than 1.2 million hectares (30% of all protected areas of Ukraine) suffer from the effects of the war. As a result of shelling, uncontrolled forest fires occur, and the amount of waste has increased catastrophically. As a result of damage to the water supply infrastructure, 1.4 million people in Ukraine currently have no access to safe water.

The state of atmospheric air is an important indicator of the ecological situation [2]. The direct and indirect impact of active military operations through the bombing and burning of forests and industrial and energetic objects causes the formation of large volumes of pollutants in the atmospheric air. According to the data of the Ministry of Environmental Protection and Natural Resources, as of January 11, 2022, estimated losses due to air pollution amounted to UAH 1,000 billion [3]. It is obvious that for a general analysis and assessment of the impact of military operations on air quality, it is necessary to use background monitoring data to display an entire perspective of air quality changes during the war. The solution to this problem is complicated by the difficult or completely closed access to environmental data due to security issues or the lack of funding for systematic monitoring.

The *purpose* of this study is to assess the change in the volume of the main atmospheric air pollutants over the territory of Ukraine compared to the pre-war period using open data of

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remote monitoring and geoinformation and cloud technologies.

2. Data and methodology

Global monitoring results with a spatial resolution near 1 km^2 which were obtained with the Sentinel-5P TROPOMI satellite instruments during 2021 and 2022 were used as input data for the study. The overall results of the previous studies [4, 5, 6] confirmed the capability of Sentinel-5P data to be used in monitoring the air quality.

The offline (OFFL) versions of air quality datasets of TROPOMI products, including the density of nitrogen dioxide NO_2, sulfur dioxide SO_2, ozone O_3, formaldehyde HCHO, carbon monoxide CO in the unit of mol/m^2 and unitless aerosol absorbing index (AAI), which represent pollution by the absorbing aerosols were used in this study. The general characteristics and sources of the input data are shown in the table 1.

Table 1. List of datasets used in the study.

Variables	Observation period	Earth Engine Snippet
NO_2	2021-2022	COPERNICUS/S5P/OFFL/L3-NO2
SO_2	2021-2022 (data are N/A in Jan and Dec)	COPERNICUS/S5P/OFFL/L3-SO2
CO	2021-2022	COPERNICUS/S5P/OFFL/L3-CO
HCHO	2021-2022	COPERNICUS/S5P/OFFL/L3-HCHO
O_3	2021-2022	COPERNICUS/S5P/OFFL/L3-O3
AAI	2021-2022	COPERNICUS/S5P/OFFL/L3-AER-AI

Google Earth Engine, a cloud computing platform, which is a modern powerful open tool for solving environmental monitoring problems, was used as an environment for data preparation and analysis [7, 8, 9]. This platform has been successfully used in various scale research [10, 11, 12, 13, 14] to analyze changes in atmospheric air quality during the lockdown due to the COVID pandemic in 2020-2021.

Additionally, for the territory of Ukraine it was investigated the changes in NO_2, CO, O_3, SO_2, and $PM_2.5$ atmospheric pollution during the first months of the full-scale war, compared to the similar periods of 2019, 2020 and 2021 [15]. The aforementioned study found a high correlation between NO_2 and $PM_2.5$ with the intensity of hostilities, an increase in CO and O_3 levels, and a significant decrease in SO_2 concentrations as the war intensified.

Therefore, taking into account previous research experience, Google Earth Engine is chosen as the optimal tool for working with large-scale observational data.

Visualization of the obtained analysis results were carried out using QGIS 3.22.14 "Białowieża".

This study included the following stages:

- downloading observed data;
- filtering and clipping data for the research area (the whole Ukraine);
- calculation and mapping of generalized monitoring results (average annual values) for 2021 and 2022;
- calculation of average monthly values of air pollutants for 2021 and 2022;
- construction of time series;
- Loading and saving spatio-temporal data for further research.

3. Results and discussions

The spatial distribution of the air pollutants is shown in figure 1.

The obtained results showed a decrease in the average annual density value for NO_2 (1.99%), CO (11.72%), HCHO (1.54%), and SO_2 (32.77%) in 2022 compared to 2021.For the average annual value of O_3 density, an increase of 1.55% is observed (figure 2).

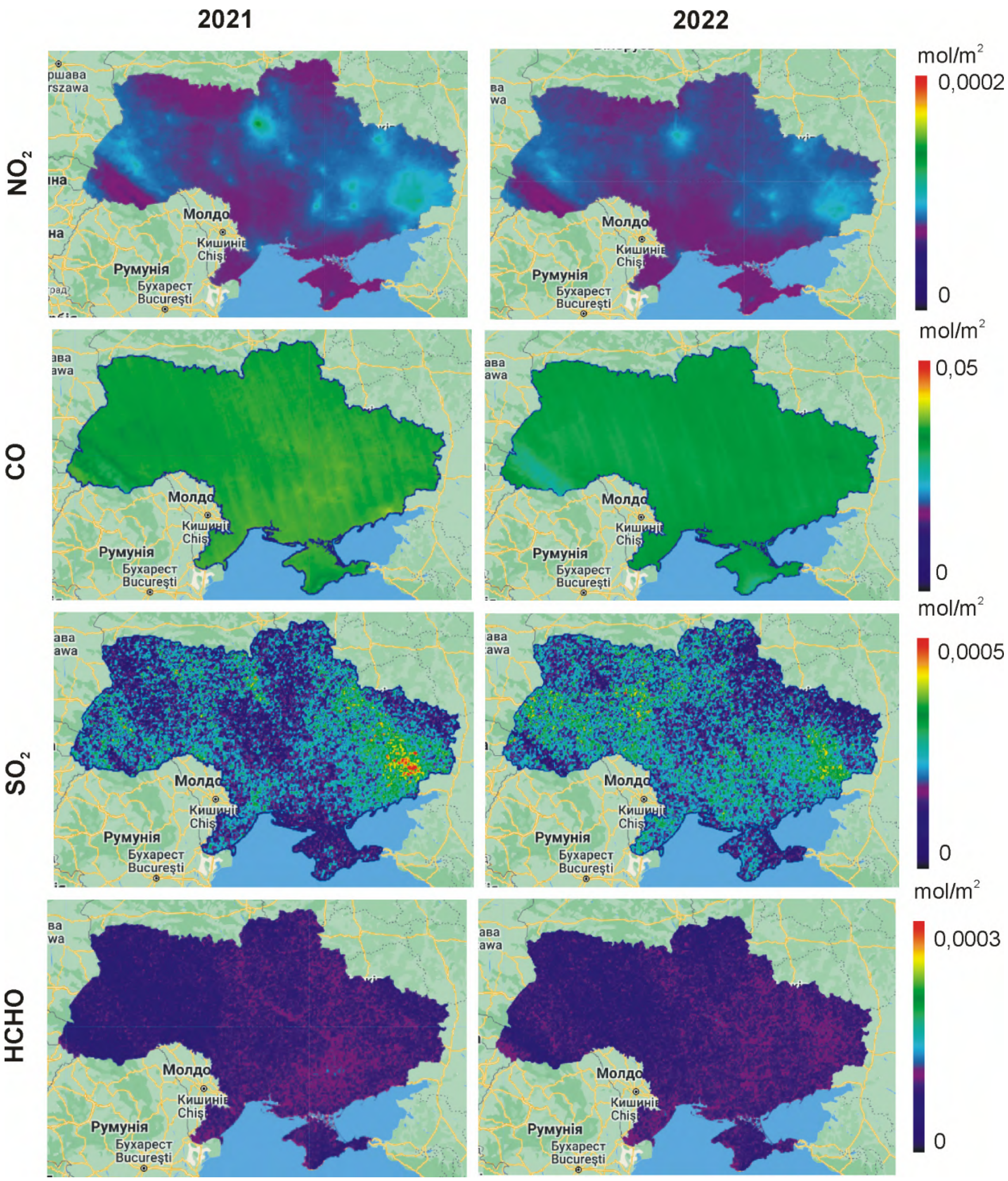

Figure 1. Spatial distribution of air pollutants over Ukraine in 2021 and 2022.

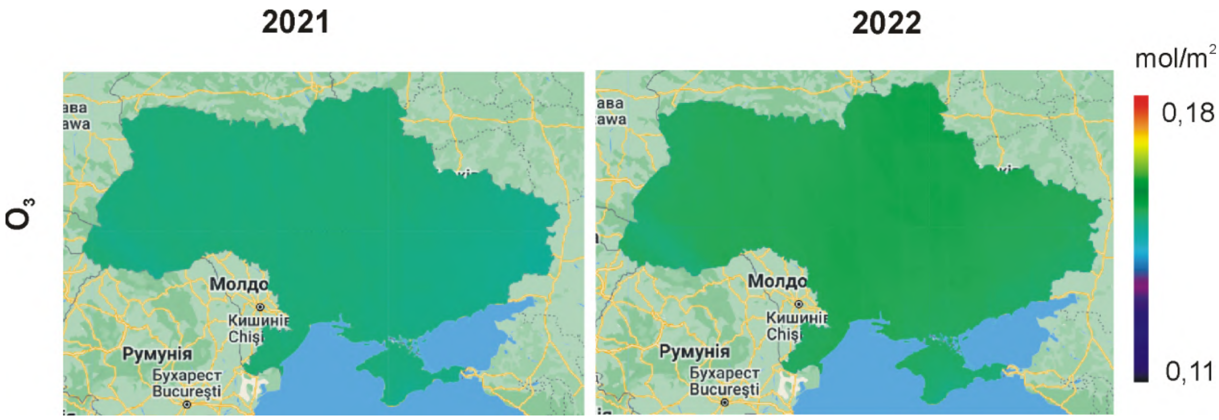

Figure 2. Spatial distribution of O_3 density over Ukraine in 2021 and 2022.

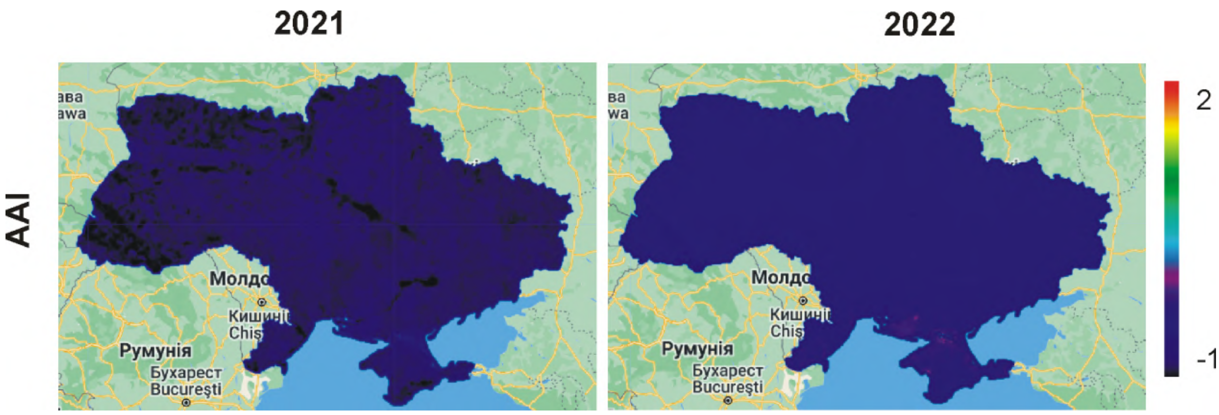

Figure 3. Spatial distribution of AAI values over Ukraine in 2021 and 2022.

The average annual value of AAI in 2022 also increased by 55.84% compared to 2021 (figure 3), which is evidence of a huge concentration of aerosols, smoke and dust in the atmosphere, resulting from explosions and fires.

Average monthly values were calculated separately for 2021 and 2022 using JavaScript language tools in Google Earth Engine to evaluate and compare the temporal dynamics of the considered variables. The created time series of the seasonal dynamics of the air quality are presented in figure 4. It is obvious that with a general tendency to decrease the amount of the considered pollutants, the seasonal patterns of its variability were preserved during 2022.

Evidently, the decrease in emissions of pollutants into the atmosphere, and therefore their content in the air, is connected with the shutdown of enterprises and is a reflection of the negative impact of military aggression on the Ukrainian economy. It should also be realized that pollution has become more dispersed in space. Emissions of specific substances occur as a result of explosions, which settle in soils, surface waters, migrate into bottom sediments and groundwater[16, 17, 18]. Thus, a necessary step will be to conduct a diagnostic assessment and analysis of the specific pollutants content (in particular, heavy metals, carcinogens, etc.) with the involvement of the developed investigated methods of individual environmental components [19, 20, 21, 22].

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Figure 4. Monthly average density of pollutants, O_3 and AAI over Ukraine (2021-2022).

4. Conclusions

The study of changes in the values of NO_2, CO, O_3, SO_2, HCHO density in atmospheric air and the absorbing aerosol index (AAI) as a result of military operations for the territory of Ukraine were conducted using the Google Earth Engine cloud geoinformation platform and remote sensing data of the Sentinel-5P TROPOMI.

The study of the distribution of pollutants showed declining annual mean values of NO_2, CO, SO_2, and HCHO in 2022 compared to the 2022 year. In contrast, overall higher O_3 was observed. The AAI increasing significantly.

The obtained results are a clear indication of the armed conflict's impact on air quality, the health of the population and the environment in general. They are important for conducting audits and designing an environmental monitoring system for assessing losses due to military aggression and post-war environmental restoration.

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References

[1] Ministry of the Environmental Protection and Natural Resources 2023 Briefing on the environmental damage caused by the Russia's war of aggression against Ukraine (February 23 - March 8, 2023) URL `https://ecozagroza.gov.ua/en/news/103`
[2] Yatsenko L D, Ivaniuta S P and Martiusheva O O 2012 "Indykatory stanu ekolohichnoi bezpeky derzhavy".

Analitychna zapyska ["Indicators of ecological safety of the state". Analytical note] URL http://www.niss.gov.ua/articles/993/

[3] Ministry of Environmental Protection and Natural Resources of Ukraine 2022 EcoZagroza URL https://ecozagroza.gov.ua/en

[4] Bodah B W, Neckel A, Stolfo Maculan L, Milanes C B, Korcelski C, Ramírez O, Mendez-Espinosa J F, Bodah E T and Oliveira M L 2022 *Journal of Cleaner Production* **357** 131960 ISSN 0959-6526 URL https://doi.org/10.1016/j.jclepro.2022.131960

[5] Soleimany A, Grubliauskas R and Šerevičienė V 2021 *Air Quality, Atmosphere & Health* **14**(3) 411–429 URL https://doi.org/10.1007/s11869-020-00946-z

[6] Savenets M V, Osadchyi V I and V O A 2021 *Visnyk of the National Academy of Sciences of Ukraine* (3) 50–58 URL https://doi.org/10.15407/visn2021.03.050

[7] Gorelick N, Hancher M, Dixon M, Ilyushchenko S, Thau D and Moore R 2017 *Remote Sensing of Environment* **202** 18–27 ISSN 0034-4257 Big Remotely Sensed Data: tools, applications and experiences URL https://doi.org/10.1016/j.rse.2017.06.031

[8] Amani M, Ghorbanian A, Ahmadi S A, Kakooei M, Moghimi A, Mirmazloumi S M, Moghaddam S H A, Mahdavi S, Ghahremanloo M, Parsian S, Wu Q and Brisco B 2020 *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing* **13** 5326–5350 URL https://doi.org/10.1109/jstars.2020.3021052

[9] Kumar L and Mutanga O 2018 *Remote Sensing* **10**(10) 1509 ISSN 2072-4292 URL https://doi.org/10.3390/rs10101509

[10] Dhital N B, Bhattarai D R, Sapkota R P, Rijal K, Byanju R M and Yang H H 2022 *Aerosol and Air Quality Research* **22**(8) 220201 URL https://doi.org/10.4209/aaqr.220201

[11] Behera M D, Mudi S, Shome P, Das P K, Kumar S, Joshi A, Rathore A, Deep A, Kumar A, Sanwariya C, Kumar N, Chandrakar R, Seshadri S, Mukherjee S, Bhattaram S K and Sirivella Z 2021 *Geocarto International* 1–21 URL https://doi.org/10.1080/10106049.2021.1993351

[12] Ghasempour F, Sekertekin A and Kutoglu S H 2021 *Journal of Cleaner Production* **319** 128599 ISSN 0959-6526 URL https://doi.org/10.1016/j.jclepro.2021.128599

[13] Wang S, Chu H, Gong C, Wang P, Wu F and Zhao C 2022 *International Journal of Environmental Research and Public Health* **19**(24) 17056 ISSN 1660-4601 URL https://doi.org/10.3390/ijerph192417056

[14] Xing H, Zhu L, Chen B, Niu J, Li X, Feng Y and Fang W 2022 *Earth Science Informatics* **15**(2) 863–876 ISSN 1865-0481 URL https://doi.org/10.1007/s12145-021-00739-7

[15] Zalakeviciute R, Mejia D, Alvarez H, Bermeo X, Bonilla-Bedoya S, Rybarczyk Y and Lamb B 2022 *Sustainability* **14**(21) 13832 ISSN 2071-1050 URL https://doi.org/10.3390/su142113832

[16] Heruk Y V, Kuzmenko E, Davybida L, Yakovlev Y O and Nikitash A P 2017 About a temporal relation between precipitation and groundwater levels on the right bank of the Kiev hydroelectric reservoir *16th International Conference Geoinformatics - Theoretical and Applied Aspects* (European Association of Geoscientists & Engineers) ISSN 2214-4609 URL https://doi.org/10.3997/2214-4609.201701811

[17] Davybida L, Worsa-Kozak M, Górniak-Zimroz J and Michalak A 2021 Spatial and Temporal Trend Analysis of Meteorological, Hydrological and Hydrogeological Data (by the Example of the San River Basin) *International Conference of Young Professionals, GeoTerrace 2021* (European Association of Geoscientists and Engineers, EAGE) ISSN 2214-4609 URL https://doi.org/10.3997/2214-4609.20215K3039

[18] Kuzyk A, Karabyn V, Shuryhin V, Sushko Y, Stepova K and Karabyn O 2023 *Ecological Engineering and Environmental Technology* **24**(1) 46–54 URL https://doi.org/10.12912/27197050/154909

[19] Zaporozhets A O, Sverdlova A D, Ivaschenko T G, Kovach V O and Artemchuk V O 2022 *IOP Conference Series: Earth and Environmental Science* **1049**(1) 012016 URL https://doi.org/10.1088/1755-1315/1049/1/012016

[20] Pohrebennyk V and Dzhumelia E 2021 *Ecological Engineering & Environmental Technology* **22**(4) 39–44 ISSN 2719-7050 URL https://doi.org/10.12912/27197050/137872

[21] Gardner-Frolick R, Boyd D and Giang A 2022 *Environmental Science & Technology* **56**(5) 2843–2860 URL https://doi.org/10.1021/acs.est.1c01739

[22] Yan T, Shen S L and Zhou A 2022 *Environmental Pollution* **308** 119611 ISSN 0269-7491 URL https://doi.org/10.1016/j.envpol.2022.119611

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On the coherence of the formation of containing and ore containing Precambrian formations Orikhovo-Pavlograd suture zone of the Ukrainian shield

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On the coherence of the formation of containing and ore containing Precambrian formations Orikhovo-Pavlograd suture zone of the Ukrainian shield

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Abstract. This paper presents the results of detailed geological and structural surveys within the Orikhovo-Pavlograd suture zone of the Ukrainian shield. In the northern part of the Orikhovo-Pavlograd suture zone of the Ukrainian shield, dislocation structures of several generations are identified, which differ from each other in spatial placement and R-T values of material filling. The structures of the first five generations are formed by mineral parageneses from granulite to green shale facies of metamorphism; their age is connected to the time range of 3.6–1.8 billion years. Later dislocation structures are postmetamorphic. At the micro-meso levels of the organization, the selected structures are represented by striation, shale, linearity, cleft, cracks, etc.; at the macro level, they are represented by viscous and brittle faults. Systematized data on the structural and material organization of U-, Th-containing Pivnichno Tersyansk folded shape according to the principle of hierarchy of geological structures. It is shown that this U-, Th-perspective object is a highly ordered propulsion structure. That is, its formation was provoked by Paleoproterozoic displacements and occurred synchronously with the formation of containing geological bodies by turning up existing Precambrian formations with the creation of new structural and material parageneses. An idealized model of forming a single U-, Th-perspective structure is created, this will contribute to the search for uranium-thorium mineralization and the expansion of the mineral resource base of nuclear energy in Ukraine.

1. Introduction

The Orikhovo-Pavlograd suture zone crosses the Ukrainian shield (US) in a submeridional direction and traces beyond its borders. It has a deep structure in the form of a package of tectonic plates of subvertic fall. Within the US, this suture zone can be traced at a distance of up to 200 km with a width of 40 to 4 km and separates the Serednioprydniprovsky and Pryazovsky Megablocks of the US. The Orikhovo-Pavlograd suture zone differs from adjacent

Megablocks in the nature of the manifestation of the Moho interface surface – within the zone it is fixed in the depth range of 42-46 – 53 km, in Megablocks – at the level of $\sim$ 40 km [1]. But the zone is most clearly distinguished relative to Megablocks as a deep linear zone of increased electrical conductivity [1].

According to [2], the depth of the sole of the "Granite" layer of the Earth's crust within the studied part of the gorge is $\sim$ 10-15 km.

The depth of the sole of the transition layer for the Orikhovo-Pavlograd zone is 25-30 km; the depth of the erosion section is determined at 17-20 km [2].

The zone is filled with an association of crystalline rocks, generally similar to such adjacent Megablocks, at the same time, it is characterized by characteristic (suture) structural and material features [1, 3, 4]. The following age figures are known for geological bodies of the zone: 3.6, 3.2, 3.0, 2.8, 2.0, 1.9 billion years [1,3,5–8].

The Orikhovo-Pavlograd zone is identified [1] with the zone of collision of the Pryazovsky and Prydniprovsky microcontinents at the archaea Proterozoic boundary and is interpreted, together with the adjacent edge parts of Megablocks, as regions of permanent stretching-compression of the crust. In other words, these are areas of more intensive processing of the epiarchean foundation, compared to the central parts of Megablocks.

The western border of the zone is considered to be the Orikhovo-Pavlograd deep fault, which runs far beyond the US (to the Kursk magnetic anomaly area), because it is clearly expressed in physical fields. According to deep seismic sounding data, a ledge of the Moho section with an amplitude of 8 km is recorded in the fault zone (at Chapter 44-46 km). Gabbro-peridotites of the Novopavlivsky section and the Malotersnyansky alkaline massif are associated with this fault. The Orikhovo-Pavlograd fault has an inclined-stepped displacement surface, which is formed from structures of higher orders with an easterly fall. The angles of incidence vary from 70-80° in the near-surface part of the foundation to 40° in the upper mantle. The eastern boundary of the zone is considered to be the West-Azov (Azov-Pavlograd) fault, it is also well expressed in physical fields and is fixed by the gravitational step. The fall of the fault offset in the upper parts of the crust (0-3 km) is subvertic, and with depth it becomes more inclined with a fall to the West [1].

According to Gintov [9], the kinematics of the Pavlograd fault zone is determined as follows: the zone was formed as a right horizontal shift ($\sigma_1 - 20/0, \sigma_3 - 290/0, \sigma_2 - \perp$) and activated as a left Skido-zdvig ($\sigma_1 - 275/30, \sigma_3 - 35/50, \sigma_2 - 155/45$). The age of this fault zone is considered by Gintov as neoarchean, since it intersects and deforms by the Devladovsky fault zone; according to the latter, neoarchean hyperbasites took root in the Earth's crust.

According to Kruglov et al [4], The Orikhovo-Pavlograd zone, like other suture zones of the gorge, differ sharply in formation content, but usually only in dislocation intensity and other features from one of the adjacent Megablocks, while at the same time they have many common features with the other. That is, according to the authors [4], suture zones are not peer-to-peer with Megablocks and independent structural-formation zones. In particular, the Orikhovo-Pavlograd zone (synclinor zone) occupies the westernmost part of the Priazovsky megablock and borders the West Priazovsky anticlinor zone along the Korsatsky and Pavlograd deep faults.

Within the Orikhovo-Pavlograd suture zone, known uranium (thorium-uranium) mineralization is represented by a small number of ore occurrences of uranium (thorium-uranium) hydrothermal in mineralized zones of crushing of crystalline rocks of the ore formation. It mainly tends to its western parts within the Orikhovo-Pavlograd deep fault, these are the Pivnichno Tersyansk, Vasynivsky, Novopavlivsky ore occurrences, etc. [8].

2. Results and discussion

The authors of the article carried out detailed geological and structural works in the northern part of the Orekhovo-Pavlograd seam zone (River Vovcha Basin , next to the village Vasylkivka),

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where feldspar quartzites, Garnet-biotite gneisses, tonalites–tonalito-gneisses, and granitoids were studied in quarries. It is established that deformation formations of 7 generations are manifested in all the studied rock varieties. These are banding, slitting structures, shale formation, several generations of mineral linearity, and brittle cracks. The actual material on the placement of metamorphogenic structures was processed using the StereoNett 2.46 program; the Pivnichno Tersyan folded shape was also characterized in accordance with the principle of hierarchy of geological structures.

Generation structures-1 expressed as relict lenticular subtiles among later dissection planes. Such bodies of various sizes – from several *see* up to the first meters; the ratio of their long axis to the short one (**a: C**) reaches 7. Axis **a** obliquely submerged in azimuth 330-0 (1 in figure 1).

For quartzites, these are close to massive bodies of essentially quartzite composition, which are distinguished by shades of colors ranging from dark gray to light gray, almost white (L_1 in

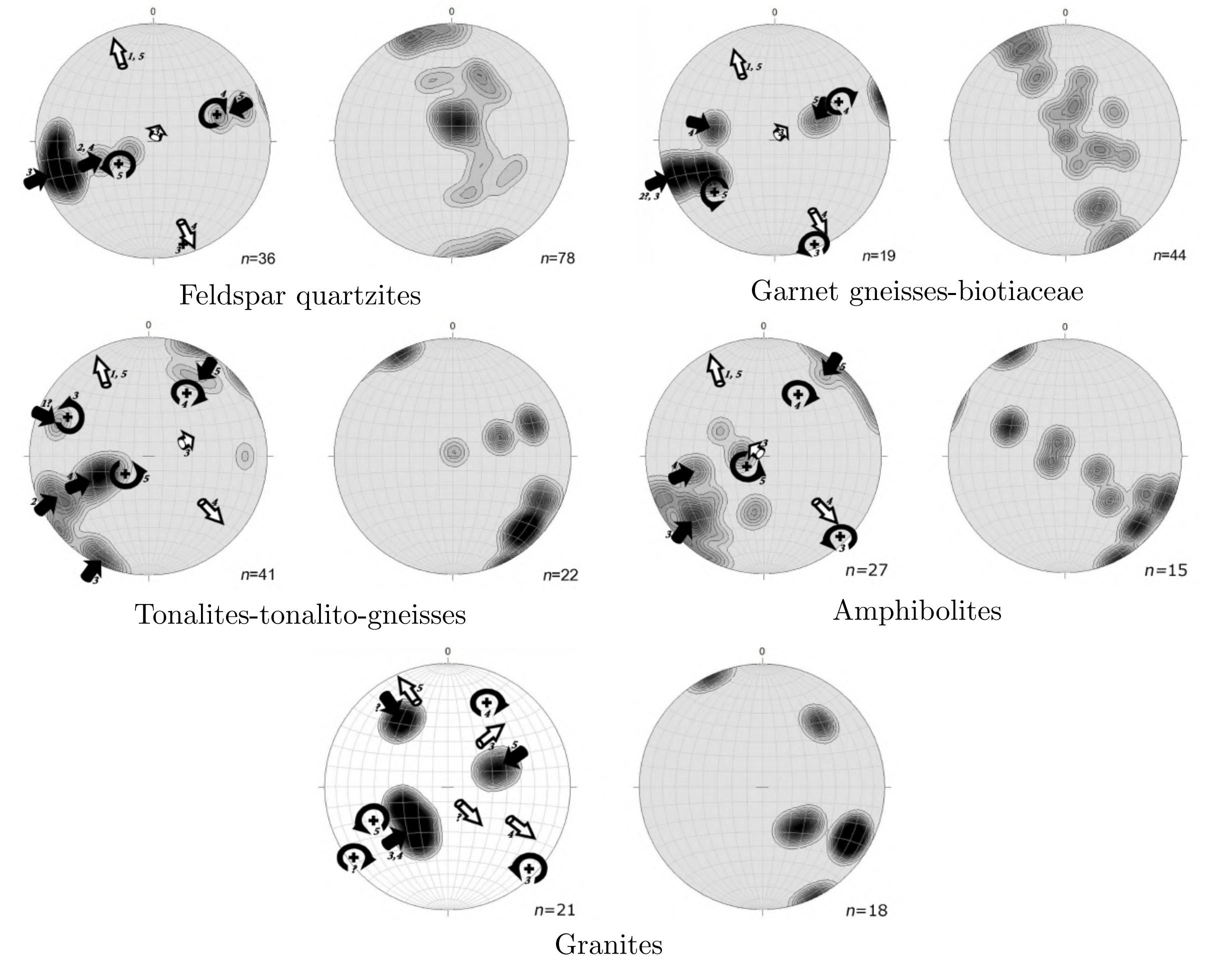

Figure 1. Stereograms of the poles of the planes of striation and shale formation and immersion of linearity along mineral aggregates and folded axes for conducting petrotypes of the Orikhovo-Pavlograd suture zone. Projection on the lower hemisphere. Gradation of isolines: 1-2-3-4-5-6-7-8-9-10-11-12-13-14-15. Arrows – directions of action of tectonic stresses (for simplification shown by one Arrow): Black straight lines – compression, white lines – stretching; rounded lines – rotation, crosses – their axes. The numbers next to it are the stage index. n – number of measurements.

figure 2).

For geological bodies of Garnet-biotite gneisses, relict formations are poorly diagnosed by shadow linearity in the separation planes, which is expressed as the division of rock into dark and light gray fractions (L_1 in figure 3). In tonalites–tonalites-gneisses, the structures of this generation are represented by elongated massive bodies of the tonalite composition (figure 4 marked – t), enderbites, and amphibolites.

Generation structures-2 they are most clearly expressed in tonalito-gneisses and are represented by striation, which is due to variations in the mineral composition. Banding has a dip azimuth of planes of ~ 70, < 80-90. The thickness of the strips does not exceed 1 cm (2 in figure 1 A and Y_2 in figure 4).

In Feldspar quartzites, the structures of this generation include one of the shale formations formed by rock-forming minerals and their lenticular aggregates (figure 2); it has elements of occurrence similar to banding in tonalito-gneiss. The structures of this generation also include linearity, which sinks at angles of $\sim 45°$ in both quartzites and biotite gneisses (L_2? in figure 2, figure 3).

Generation structures-3 it is represented by striation and shale with steeply falling mineral linearity. The banding of this generation is most clearly distinguished in geological bodies of the composition of tonalites–tonalites-gneisses and Garnet-biotite gneisses. In tonalito-gneiss, these are Lenses strips with capacities of several cm (3 in figure 1, Y_3 in figure 4) granite composition, which are secant to the structural elements of previous generations in several degrees. In garnet-biotite gneisses, these are leuco- and melanostripes. The first of them are quartz-feldspar composition, the second correspond to gneiss proper (figure 3). The shale content of this generation is well expressed in Feldspar quartzites; it is formed by rock-forming minerals and their aggregates (figure 2).

Mineral linearity of Generation-3 in tonalito-gneisses is weakly expressed; it is most clearly distinguished in geological bodies of the composition of Feldspar quartzites by elongated aggregates formed by feldspar, biotite and garnet; in bodies of the composition of Garnet-biotite gneisses, linearity is relatively moderately expressed by elongated aggregates of biotite and Garnet (3 in figure 1; L_3 in figure 2, figure 3). The size of such units is from several to 8 mm, **a: c** – 5-7, their placement reproduces subvertic chains several tens of centimeters long.

Generation structures-4 for all the studied breed varieties, they are represented by separation. They are expressed by a shale matrix (actually dissociation zones), which contains lenticular bodies subordinate to it with a relatively massive structure. The separation planes are formed by single-system placement of flat grains and aggregates of rock-forming minerals. Dip azimuth of planes shale/slotting planes ~ 70 at angles of about 40. For quartzites, the dissection structures are expressed as alternating shale feldspar quartzites and close to massive quartzites (figure 2). For Garnet-biotite gneisses, the dissection structures are represented by separate gneiss dissection zones that distinguish the striped gneisses themselves. The capacities of such zones are the first *see*, the distance between them reaches several tens of centimeters – the first meters. For tonalites–tonalites-gneisses, the shale Matrix corresponds to gneisses of the tonalite composition (tonalite-gneisses). Packages of shale tonalito-gneiss reach capacities from several meters to several tens of meters (figure 4). Such packages contain lenticular bodies of the composition of tonalites and enderbites and striped tonalites, as well as folded-lenticular bodies of the composition of amphibolites with dimensions of tens *see* – first meters.

In the shale planes, there is a mineral linearity that sinks obliquely to the Southeast (4 in figure 1). In Feldspar quartzites, this linearity is formed by Muscovite aggregates; in garnet-biotite gneisses-Muscovite and biotite (L_4 in figure 2, figure 3); in tonalites – tonalites-gneisses, linearity is represented by hinges of folded bodies of amphibolites and elongated spindle-shaped aggregates of quartzite composition. The dimensions of the latter along the long axis reach 20 cm, **a: C** exceeds 10 (figure 5).

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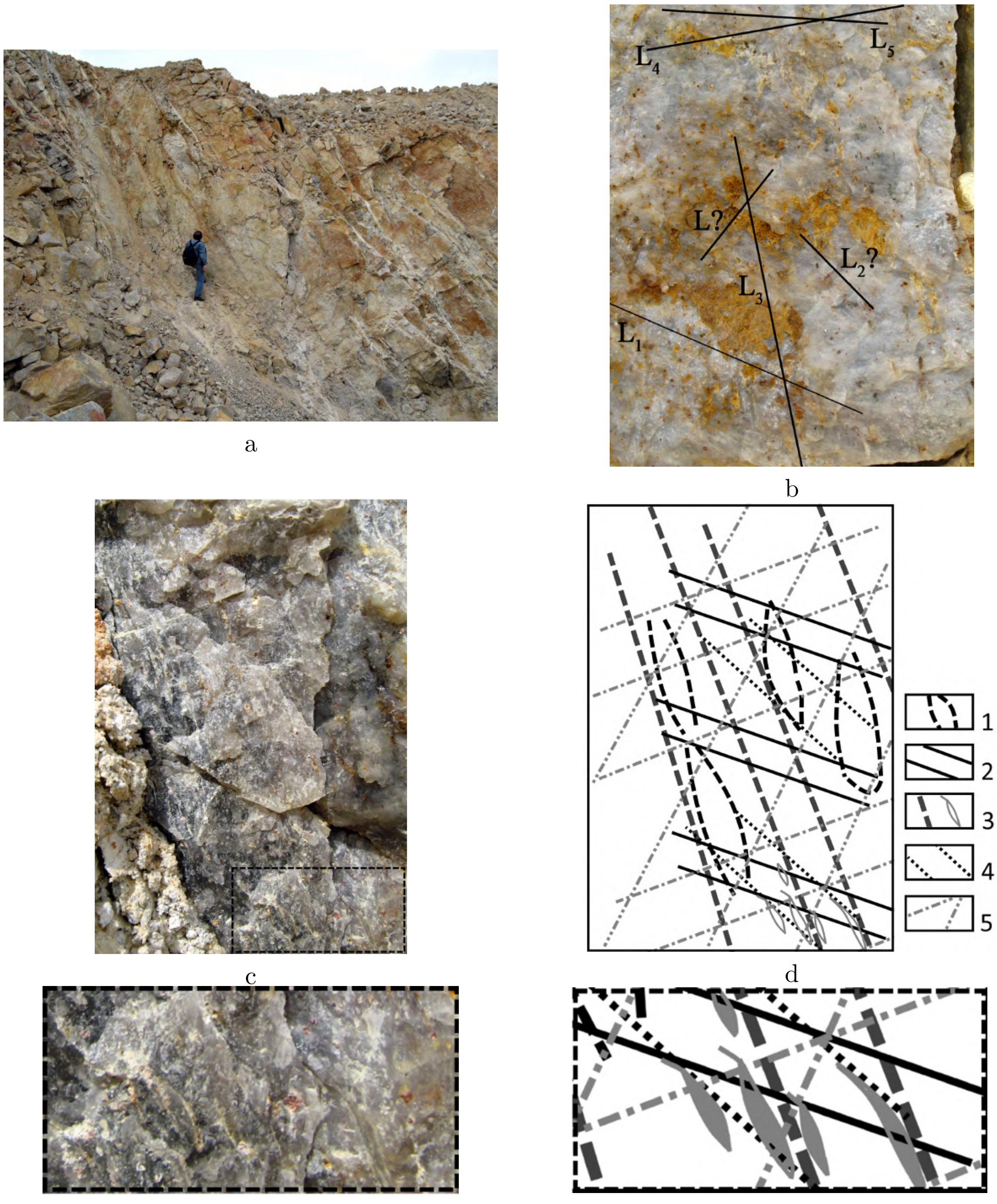
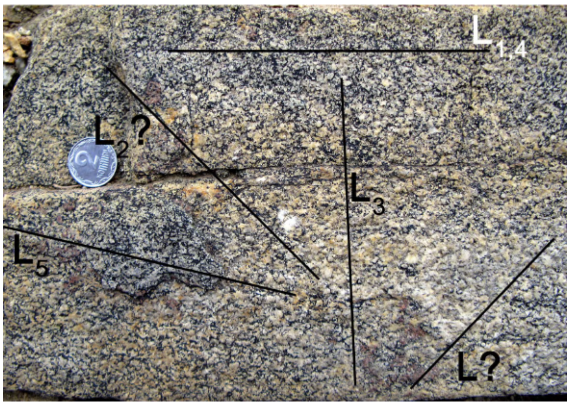
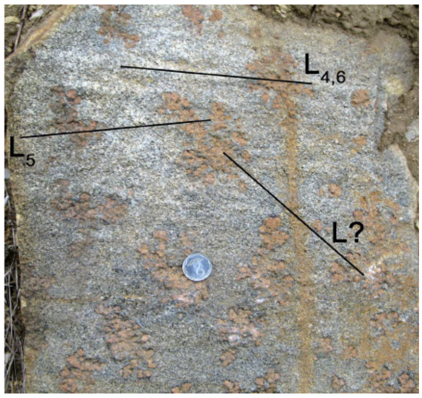


Figure 2. Multi-stage structure of Feldspar quartzites of the Orikhovo-Pavlograd suture zone. a – general view in the vertical plane – **b: c** Y_4 (exposure South), visible lens L_1; b – in the plane **a: b** Y_4, where you can see several generations of linearity (underlined with lines; vertical slice, eastern exposure. Scale – coin 10 kopiyok); c, d – a larger image in the plane **b: c** Y_4, where c is a photo, d is a schematized sketch (for the scale – pomegranate seeds with dimensions of 2 – 5 mm). The frame highlights the part shown in figures e, f 1 – 5-metamorphogenic dislocation structures of the corresponding generations.



a



b

c

d

Figure 3. Multi-stage structure of Garnet-biotite gneisses of the Orekhovo-Pavlograd suture zone. a, b – linearity (underlined by lines) of several generations in subvertic planes of separation: L_1 – 5 – mineral linearity, L_6 – behind the barbs of sliding (a – exposition eastern, B – Western). B-striation (Y_3) in the vertical plane transverse to it and subsequent generations of shale formations ($Y_{4,5}$). d – enlarged part to figure in, where it is clearly visible that shale is formed by rock-forming minerals; concentric aggregates corresponding to the roles of the third stage are also visible (southern exposure). Scale – 2 kopiyok coin.

Generation structures-5 they are represented by single planes of separation (5 in figure 1; Y_5 in figure 4), which fall relatively steeply to the West. They are also formed by rock-forming minerals. The distances between such planes are measured in tens of centimeters. They carry a mineral linearity that sinks obliquely to the northwest (L_5 in figure 2,3). In quartzites, it is expressed by sericite scales.

Generation structures-6,7 to varying degrees, they are manifested in all the studied

Figure 4. Multi-stage structure of tonalito-gneisses of the Orikhovo-Pavlograd suture zone: a – striation of two generations-$Y_{2,3}$ and shale formation Y_5. In the center of the outcrop is a lenticular body close to a massive one (L_1) composition of tonalite-T (vertical cut in the plane **b: c**, northern exposition); b – flaking/de-lensing-Y_4, T-lenticular bodies of tonalite composition (sub-horizontal section, western exposure); c – linearity (L_1) along the axes of folded bodies of amphibolites, singranitization striation ($Y_{2,3}$), lensing and building (Y4b-internal lined structure of the amphibolite structure with leucocratic secretions in the form of asymmetric lenses and hooks. This structure indicates the formation of amphibolite bodies by shear transformations (the plane is close to horizontal)).

varieties of breeds. These are fragile cracks, narrow (with several capacities mm – the first ones *see*) zones of crushing, cataclysm and milonitization of rocks. Within such formations, no dynamometamorphic changes in rocks are recorded, so they are not displayed on stereograms, but they are visible in figure 2, 4. The elements of occurrence of structures of this generation are as follows: dip azimuth of planes $\sim$ 0, $<$ 45, 80; dip azimuth of planes $\sim$ 190, $<$ 0 – 45; dip azimuth of planes 270, $<$ up to 40; dip azimuth of planes $\sim$ 70, $<$ 80-90. The latter planes contain beard and linearity in sliding strokes. The first of them sinks obliquely, the second up

a

b

Figure 5. Linearity (L_4) formed by aggregates of quartzite composition in a shale matrix of tonalito-gneiss composition: a – vertical section in the plane **a: b** Y4 (western exposure); b – vertical cross-section in the plane **b: c** (transverse to shale, southern exposure).

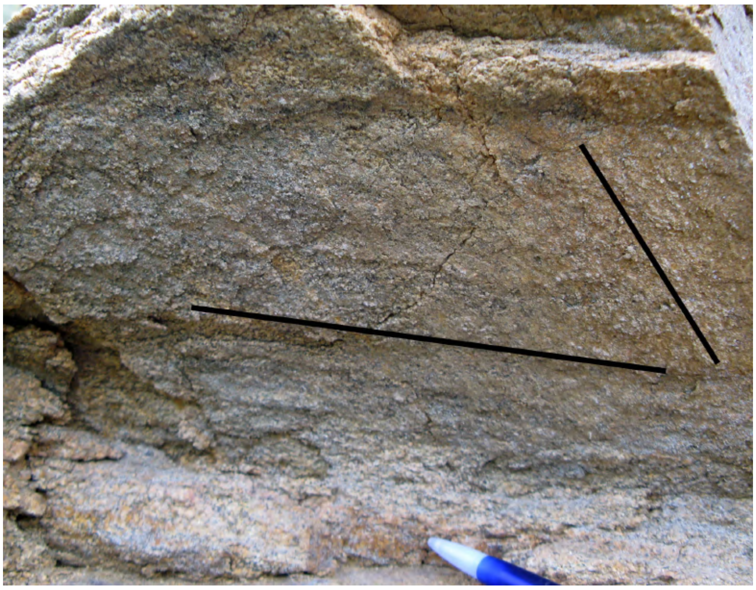
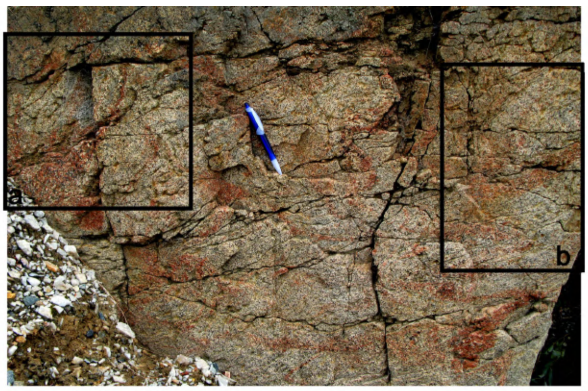


Figure 6. Two generations ($L_{6,7}$) linearities (underlined by lines) in the submeridional planes of the separation of tonalito-gneiss, represented by striations, and sliding strokes. Western exposure

to 45 in the southern points (figure 6).

Geological bodies of granites and amphibolites also have a hybrid structure similar to that of tonalito-gneisses and garnet-biotite gneisses (figure 1, figure 7). The amphibolites are found as very dispersed lenticular-house bodies of various sizes among the shale matrix of the tonalito-gneiss composition (figure 4). We have not recorded geological bodies of granite composition in the form of single manes and their immediate boundaries with formations of a different composition. But these "manes" of granite composition in the transverse (up to the leading shale) cross-section have an inhomogeneous, striped-folded internal structure (figure 7). The latter is expressed by lenticular subtiles with internal drawing folds and resistances that reproduce the right-wing structural pattern. The base of this pattern is formed by white granites, the contours of lenses, folds and feather are formed by red ones. At the same time, the ribbon-like bodies of red granites are not injections, the boundaries between them and white granites are gradual, and the shale of white granites is subordinated to the structural pattern formed by the striation of red granites.

The latter is often divided into quartz and feldspar fractions, and the cores of folded forms contain sickle-shaped clusters of dark-colored minerals.



A

B

Details for figures a, b, which are framed in figure A.

Figure 7. Internal structure of granitoid bodies: a – a photo where the details shown in the lower part of the figure are framed; b – the same thing – a sketch where (for simplicity) only ribbon-shaped bodies of red granitoids are displayed. Arrows – restored directions of displacements during the formation of reflected granitoids. The cut is vertical, the exposure is northern.

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All this indicates that the formation of both types of granites occurred simultaneously due to synshifts structural and material transformations.

From time to time, fairly dispersed shale planes can be traced within the granitoids, falling to the northeast and west – southwest. That is, shale is similar to that of generations 4 and 5 in other types of rock bodies. Therefore, it can be assumed that folding with material transformations in granitoids occurred at the third stage of structural-material transformations of the studied part of the suture zone.

Thus, in all rock varieties of geological bodies within the part of the studied zone, the same structural and material paragenesis was manifested. They are the same in terms of spatial position, the number of generations of structural elements, and R-T implementation conditions. Consequently, all the studied rock varieties of the Orikhovo-Pavlograd zone were formed similarly and gradually, structural and material transformations in their volumes occurred cooperatively/simultaneously, in several stages under significantly shifted tectonic conditions against the background of regressive changes in the R-T parameters of the medium. Moreover, such transformations took place together in the entire volume of the suture zone fragment under study – from the micro - to macro-level of its petro-structural organization. The latter is evidenced by the self-similarity of structural forms at all levels of subordination for all geological bodies studied. That is, the studied volume of crystalline rocks is the only dislocation system that was formed during at least five stages of structural and material transformations of the crystal base.

The formation of the studied dislocation structures occurs in a shift environment [9–11], that is, their shape and placement are subordinated to the directions of action of tectonic stresses. At the micro level, these structures are formed using diffusion, filtration and other mechanisms of substance movement. Accordingly, their material filling reflects the conditions of formation of the studied structures. According to [5–7], the degree of metamorphism of the substance of dislocation formations reached granulite and amphibolite facies. Therefore, with age ranges 3.6; 3.4-3.3; 2.8-2.7, 2.0 billion years [5–7] and 1.9 [8] billion years we associate the formation of the metamorphogenic dislocation structures described above. According to Goryainov et al [12], we link the structures of generation-3 to the timestamp $\sim$ 2.8 billion years ago, generation-4 $\sim$ 2.0, generation-5 $\sim$ 1.9-8 billion years ago.

Pivnichno Tersyansk folded form of the Orikhovo-Pavlograd suture zone as its around shift component

Under tectonically active conditions, which are recorded in variations in the spatial position and P-T values of the creation of the studied structures, the ore substance could not be unused to the above-described transformations of the Precambrian Foundation. And ore bodies within the suture zone could be created only under tectonic conditions, under which both the containing rocks and the entire part of the foundation under study were formed. This is evidenced, for example, by the data systematized for *Pivnichno Tersyansk folded shape*, based on the materials of works [1, 8]. They are listed below in paragraphs 1-5, starting from the macro level of the petro-structural organization of the object (point 1), ending with the micro level (point 5). For such systematization, the Pivnichno Tersyansk folded form was chosen because it was relatively well studied by previous researchers due to the fact that this structure contains a deposit of ferruginous quartzites, ore occurrences of uranium and thorium, and manifestations of other mines [1, 8]. In addition to the above, the Pivnichno Tersyansk folded form is composed of rock associations similar to those that we studied within the Vasylkivska site.

1. The Pivnichno Tersyansk folded form at the macro level is expressed by two components-linear (plate – shaped) and sub-ring-shaped. The elements of the first of them are subordinated to the following elements of the Orikhovo-Pavlograd suture zone as a whole

(figure 8). Namely, the linear component has an dip azimuth to the southeast at an angle (<) of 80-85° with an extension of up to 2 km and a power of ∼ 0.5 km [1, 13]. It is traced to a depth of ∼ 0.5 km. The sub-ring component (brachisincline according to [13]) reaches a diameter of 1.0 km. Its axis has a near – latitude direction, the fall of the wings in the southern part of the brachisincline is close to vertical, in the northern part-a fall to the south at < 50-60° [13].

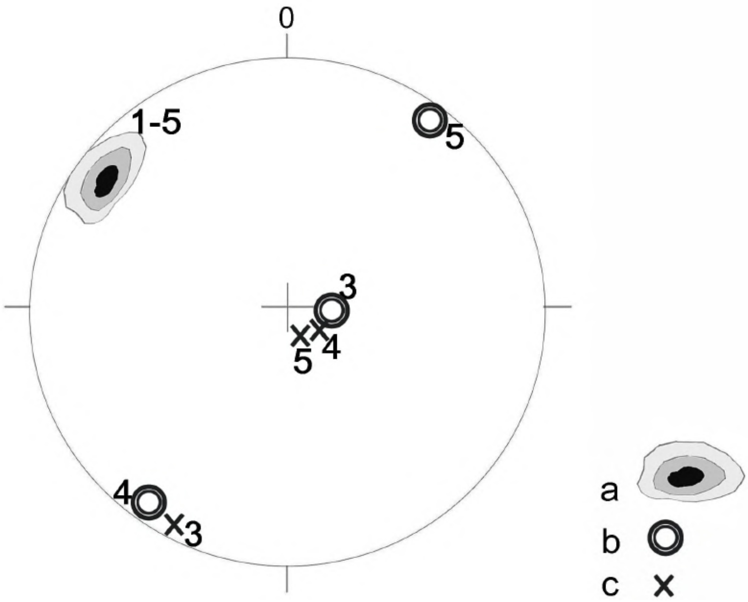

Figure 8. Schematized diagram of the placement of planar and linear structural elements for the Pivnichno Tersyansk folded shape, according to data from [1, 13] in the projection on the lower hemisphere. a – the pole of a linear (plate – like) macro-component; b-metamorphogenic linearity (tensile axes), respectively, of the above (in figure 1) data; c – projections of rotation axes. Digits – numbers of structure generations.

If we start from the fact that the linear and sub-ring components of the Pivnichno Tersyansk folded form were formed interrelated, in several stages (as well as the contained geological bodies of figure 1-figure 7), then the linear component is the zone of secondary striation and separation of stages 3-4; its pole is the point of application of tectonic compression forces. The placement of the rotation axes of generations-4 and 5, however, is close to vertical (even if the tension axes are placed sub-wide, according to the placement of the axis of the sub-ring component). That is, it follows from these data that the sub-ring component of the Pivnichno Tersyansk folded shape was formed due to the propulsion rotation of metamorphogenic strata. Accordingly, in this component, relative to the linear one, petro-structure formation occurred at lower R-T indicators of the medium. The elongated tail of the sub-ring component indicates a left-hand rotation, which we associate with the fifth stage of structural and material transformations of the studied part of the foundation; this is about 1.9-8 billion years ago. In the tail section, as a marker of relative compaction, there is a granite massif. The model of formation of such structures is recorded in natural models of structure formation (figure 7).

2. At the meso-level, both components, linear and sub-ring, of the Pivnichno Tersyansk folded shape are formed by consistent stratal-lenticular geological bodies with elements of occurrence that are similar to those for macro-composite ones. Mesotil capacities range

from a few meters to 70 m with a horizontal length of tens of meters to several kilometers. That is their **a: c** (the ratio of the long axis to the short axis) reaches 10.

Material, within the linear macro-component, geological bodies of the meso-level are represented by amphibolites, modified to varying degrees by ultramafic rocks, chloritized amphibol-magnetite quartzites and quartz-magnetite shales. Within the sub – ring component-biotite, biotite-garnet, biotite-silymanite gneisses, feldspar and glandular quartzites.

According to the studies [10,14], as well as ours, which are given above, the formation of the above-described structure of the Tersyansk folded shape is possible due to the involvement of the primary crystal base in repeated deformations of shear-stretching and scrolling of its individual fragments. That is, it is a secondary stratification – tectonostratification of the geological environment **a: c** it is an expression of the degrees of elongation of geological bodies under such deformations; the degree of metamorphism is an indicator of the P – T conditions of the dislocation process. In this case, in the linear macro-component of the Tersyansk folded form relative to the sub-ring form, the degree of metamorphism is higher, which is one of the confirmations of increased strain pressures within the linear component at the time of formation of the Tersyansk form as a whole.

3. Geological bodies of the meso-level, both in linear and sub-ring components Tersyansk folded shape, striped and slate [1, 13]. The striping is caused by changes in the mineral composition and dimensions of mineral grains; the capacities of pronounced banding in this way range from a few millimeters to several centimeters. Shale formation is caused by the single-system placement of flat minerals and their aggregates.

   As shown above, we have identified several generations of striation, shale, and mineral linearity. All of them are more or less manifested in all varieties of breeds. But the most intense is the shale formation and linearity of generation-4, which actually creates a mutual agreement of all geological bodies.

   Striation and shale formation and their coherence are expressions of the shear/stretch process at the micro level. At this level it is realized due to syndeformational recrystallization in the direction of relatively reduced strain pressures [15, 16].

4. Accordingly, [8] uranium-thorium mineralization within the Orichovo-Pavlograd suture zone is localized in layers of schistose and mylonitized chlorite-mica quartzites among micaceous quartzites of the Vovchansk Formation. According to our data, such “layers” in quartzites are the result of at least the fourth stage of structural and material transformations of the studied zone fragment.

5. In the mineral composition of the studied geological bodies, there are mineral parageneses from the granulite to green-shale degree of metamorphism [1, 7, 13]. Within the Vasylkivska site, depending on the degree of separation, the chemical composition of minerals changes [7].

   According to isotope studies [5–8], for tonalites and biotite gneisses, the age figures in 3.6; 3.4-3.3; 2.8-2.7, 2.0 for quartzites 2.8-2.7, 2.0 and for rare earth mineralization 1.9 billion years.

So, from all the above data, it follows that all the structural, material and age attributes of the northern part of the Orikhovo-Pavlograd suture zone are highly consistent. This is a consequence of tectonic-metamorphogenic transformations of this fragment of the crystalline basement in several stages. The transformations of the Fourth of the selected stages, which we link to the timestamp of 2.0 billion years ago, were most intensively implemented.

3. Conclusions

The Orikhovo-Pavlograd suture zone is a complex dislocation formation, because it was formed in several stages of tectonic-metamorphogenic transformations of the crystal base. The first five of them appeared under P-T conditions from granulite to greenschist facies of metamorphism, the next ones – at low temperatures. Despite the multi-stage and multidirectional deformation processes within the zone, its structure is dominated by submeridional anisotropy. This is due to the submeridional linearization of heterogeneous and multi-age Geological objects in the same direction [10]. Such a structure as a whole can be defined as a subvertic secondary monoclinal, reinforced with melange.

The Pivnichno Tersyansk folded form is a highly coordinated dislocation structure that was formed under significantly shifted tectonic conditions. It takes the position of a motor roll structure, which was finally created at the 4th and 5th stages of structural and material transformations of the Precambrian basis. This is about 2.0 and 1.9 billion years ago. We have attempted to restore such transformations in the form of a step-by-step model of the evolution of the structural-material pattern of the studied crystal base fragment (figure 9). Based on similar data on the structural and material organization of megablocks adjacent to the Orikhovo-Pavlograd zone [17], we form the basis of the scheme in figure 9 the vision that the Precambrian basis, within the limits of these components, at the initial stages of their formation (I – III in figure 9) had a single structural plan (the same both within the suture zone and within adjacent Megablocks). At the final stages (IV-V in figure 9) development within the suture zone was dominated by significantly shifted geological and dynamic conditions (relative to adjacent megablocks).

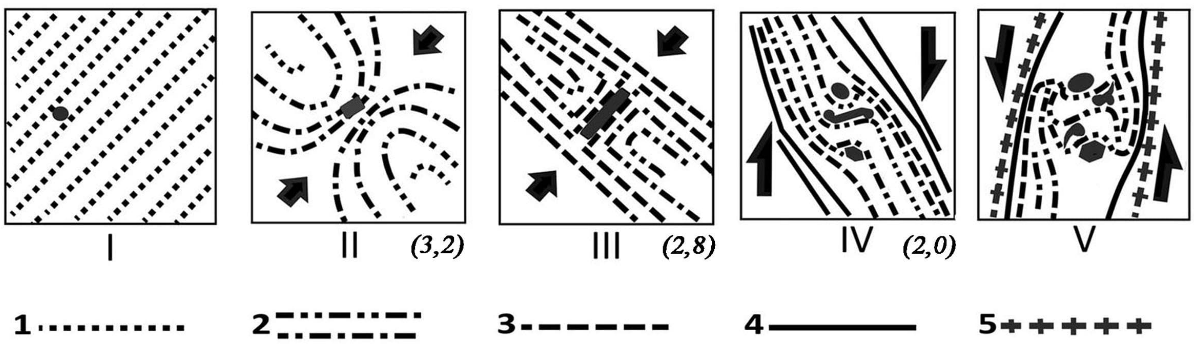

Figure 9. Schematized step by step (I-V) model of formation of the structural and material pattern of the studied part of the Orikhovo-Pavlograd suture zone. Arrows – restored directions of application of tectonic forces (in modern coordinates). 1 – 5-generation of planar structures to the appropriate stages of development of the structural plan. Gray bodies (rectangles, ovals, and irregular ones) are ore formations. 3.2, 2.,8, 2,0 – isotopic age according to their predecessors.

An idealized model of the formation of a single U-, Th- promising structure has been created, which will contribute to a more targeted search for uranium-thorium mineralization and expand the mineral resource base of the nuclear power industry in Ukraine according to the final result.

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References

[1] Azarov N Y, Antsiferov A V, Sheremet E M, Glevassky E B *et al.* 2005 *Geological and geoelectric model of the Orekhovo-Pavlograd suture zone of the Ukrainian shield* (Kyiv: Naukova Dumka)

[2] Gordienko V V, Gordienko I V, Zavgorodnyaya O V *et al.* 2005 *Ukrainian shield (Geophysics, deep processes)* (Kyiv: KORVIN Press)

[3] Esipchuk K Y, Bobrov O B, Stepanyuk L M *et al.* 2004 *Correlation Chronostratigraphic scheme of the early Precambrian of the Ukrainian shield (explanatory note)* (Kyiv: UKRSGRI)

[4] Kruglov S S, Arsiriy Y O, Velikanov V Y *et al.* 2007 *Tectonic map of Ukraine. Scale 1: 1,000,000* (Kyiv: UKRSGRI)

[5] Shcherbak N P, Artemenko G V, Lesnaya I M and Ponomarenko A N 2005 *Geochronology early Precambrian of the Ukrainian shield (Archey)* (Kyiv: Naukova Dumka)

[6] Shcherbak N P, Artemenko G V, Lesnaya I M and Ponomarenko A P 2008 *Geochronology of the early Precambrian of the Ukrainian shield (Proterozoic)* (Kyiv: Naukova Dumka)

[7] Lobach-Zhuchenko S B, Yegorova Y S, Yurchenko A V, Balahanskyi V V, Artemenko H V, Chekulaev V P and Arestova N A 2009 *Mineral* (1) 3–10 URL `http://dspace.nbuv.gov.ua/handle/123456789/61539`

[8] Gursky D S, Esipchuk K Y, Kalinin V I *et al.* 2006 *Metal minerals of Ukraine* vol I (Kyiv-Lviv: Center of Europe)

[9] Gintov O B 2005 *Field tectonophysics and its application in the study of deformations of the earth's crust in Ukraine* (Kyiv: Feniks)

[10] Patalaha E I, Patalaha G B, Osmachko L S and Tokovenko V S 2006 *Reports of the National Academy of Sciences of Ukraine* **10** 131–135

[11] Lukienko O I, Kravchenko D V and Sukhorada A V 2008 *Dislocation tectonics and tectonofations of the Precambrian of the Ukrainian shield* (Kyiv: Kyiv University)

[12] Goryainov S V, Korenev V V, Aksenov S V *et al.* 2009 *Metamorphic and metasomatic complexes of the Azov Sea and Southern Donbass* (Kharkiv: Ekograf)

[13] Semenenko N P, Ladieva V D, Bordunov I N, Boyko V L, Kutin V V, Strueva O M, Ryabokon S M, Polovko N I *et al.* 1978 *Iron-silicon formations of the Ukrainian Shield* vol I (Kyiv: Naukova Dumka)

[14] Slenzak O I 1984 *Local structures of Precambrian tension zones* (Kyiv: Naukova Dumka)

[15] Patalaha E I 1970 *Mechanism of formation of flow structures in crumple zones* (Alma-Ata: Nauka)

[16] Passchier C W and Trouw R A J 1996 *Microtectonics* (Berlin: Springer-Verlag) URL `https://doi.org/10.1007/978-3-662-08734-3`

[17] Osmachko L S 2020 *Geodynamic conditions of formation of precambrian structure and separate ore-perspective objects of the Ukrainian shield* Dis. dr. geol. science: 04.00.01 M.P. Semenenko Institute of Geochemistry, Mineralogy and Ore Formation of NAS of Ukraine, Institute of Geological Sciences of the National Academy of Sciences of Ukraine Kyiv

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Ecological adaptations among spruce species along an environmental gradient in urban areas

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Ecological adaptations among spruce species along an environmental gradient in urban areas

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Abstract. Knowledge about current state of the trees in urban areas may be important for foresting and green planting of city landscapes and for improving environmental quality in these areas. The object of this study were to screen a range of morphometric, physiological and biochemical parameters among species of the genus spruce (*Picea* A. Dietr.) in urban areas of Kryvyi Rih City and to assess the ecological adaptations among species of the genus spruce (*Picea* A. Dietr.) along an environmental gradient in urban areas of Kryvyi Rih City. During 2017-2021, the 7 research plots in Kryvyi Rih City urban areas along an environmental gradient (low, moderate and high levels of the environmental impact) and 1 research plot in the background area (control) were established. The 30–40-year-old trees of indigenous spruce species (Norway spruce (*Picea abies* (L.) Karst.)) and non-native spruce species (Colorado blue spruce (*Picea pungens var. 'Glauca'*)) were investigated. The morphometric characteristics of trees, vitality of trees and chlorophyll *a*, chlorophyll *b* content in needles were studied. The results showed that in background area the tree height (14.5-15.1 m and 11.7-12.5 m for Norway spruce and Colorado blue spruce), diameter at breast height (25.3-28.1 cm and 24.6-27.2 for Norway spruce and Colorado blue spruce), chlorophyll *a* content (0.75-1.04 mg/g of wet weight and 0.96-1.24 mg/g of wet weight for Norway spruce and Colorado blue spruce) and chlorophyll *b* content (0.33-0.41 mg/g of wet weight and 0.42-0.50 mg/g of wet weight for Norway spruce and Colorado blue spruce) were typical of mature 30–40-year-old spruce trees. In Kryvyi Rih City urban areas the ecological stress along an environmental gradient decreased the values of growth, vitalyty and photosynthetic activity of the trees by 15-50%. Colorado blue spruce trees (non-native species) exhibit greater ecological tolerance and ecological adaptations than Norway spruce trees (indigenous species). Colorado blue spruce is less sensitive to environmental impact and have a better ecological adaptive balance of pigment content than Norway spruce. Our results confirm that from a sustainable development of the urbane areas perspective it is necessary to using the Colorado blue spruce for greene planting.

1. Introduction

Today, the state of the environment in industrial cities is very critical, causes concern and requires practical measures to improve it [1–5]. The trees play an important role in improving the quality of the urban areas. Landscaping of these areas with woody plant species is an important practical measure for the implementation of sustainable development in current cities [5–9]. Among the assortment of plants, preference is given to those with high phytoncide properties [6, 10, 11]. In particular, such plants are conifers, which clean the air of harmful substances all year round, absorbing almost all types of chemical compounds entering the atmosphere with emissions from industry, energy, motor vehicles [12–15]. However, improving environmental conditions, coniferous plants themselves suffer from the negative effects of air pollutants, which leads to changes in their biological parameters, biochemical characteristics and, in general, to a decrease in their viability [6, 11, 16]. Due to this speed of reaction to pollutants substances, plants of conifers are used as environmental indicators [5, 6, 10, 13].

In Kryvyi Rih, one of the largest industrial cities of Ukraine, the level of atmospheric air pollution significantly exceeds the limits [10, 17]. Emissions from industrial enterprises and intensive traffic lead to the formation of harmful substances in the air, among which are noted: nitrogen oxides, sulfur dioxide, carbon monoxide, etc. [13–15]. The negative impact of pollution is enhanced by adverse natural and climatic conditions, which in the steppe zone are exacerbated due to climate change, which causes global warming [17,18]. It is difficult for introduced conifers to adapt to the urbotechnogenic environment of a large industrial steppe city.

Among the widespread assortment coniferous plants of Kryvyi Rih excrete out trees of spruce species, which grow all over the city in different types of plantings. In addition, they are characterized by high phytoncide activity, year-round decorativeness, attractive color of the needles [5, 6, 11]. Considering on it, the objectives of the study were (1) to screen a range of morphometric, physiological and biochemical parameters among spruce species in urban areas of Kryvyi Rih City, (2) to assess the ecological adaptations among spruce species along an environmental gradient in urban areas of Kryvyi Rih City.

2. Material and methods

2.1. The study area

The urbane areas of Kryvyi Rih City (central part of Ukraine) was chosen for the present study. It is situated between 47°53'54" and 48°8'52" north latitude and 33°19'52" and 33°33'38" west longitude. The climate of this area is characterized by short springs, hot and dry summers and cold winters with little snowy. The monthly mean air temperature ranged from -5.1°C (in January) to 22.2°C (in July). The mean annual precipitation was from 400 to 450 mm [2, 3, 16]. Kryvyi Rih is one of the largest industrial city in Europe, specializing in iron ore mining and production of iron ore concentrate, iron ore agglomerate, iron ore pellets, cast iron smelting and steel smelting. In this city the industrial activity (mining, processing and smelting operations) generate a lot of pollutants (dust, carbon / sulphur / nitrogen oxides, heavy metals) that is released into the atmosphere. The annual emissions air pollutants range from 400 000 to 700 000 tons per year [2, 17].

2.2. Research design, data collection and sampling

In our study the 30–40-year-old trees of indigenous spruce species (Norway spruce (*Picea* (L.) Karst.)) and non-native spruce species (Colorado blue spruce (*Picea pungens var. 'Glauca'*) were investigated. A systematic random sampling design was used for selection of sampling sites. The study area was divided into two locations as control area and environmental imputed area. The territory of Kryvyi Rih Botanical Garden arboretum was used as a control (sampling site 1). The environmental imputed area was divided into sub-locations as (i) low environmental impact (sampling sites 2, 3), (ii) moderate environmental impact (sampling sites 4, 5, 6) and high environmental impact (sampling sites 7, 8). All research points were located at three Kryvyi Rih City Districts such as Ternivskyi, Pokrovskyi and Metalurhiinyi. The spatial distribution of the sampling sites is shown in figure 1. Field data were collected through direct enumeration and measurement of 30-40 trees in every sampling site [19]. In each site, the tress were recorded and: (i) their diameter at 1.3 m above ground (in two perpendicular directions by a caliper); (ii) their height (by a hypsometer), (iii) the crown height and diameter (in two directions: east-west, south-north) were measured and (iv) their vital state was assessed (by Yarmishko [20]). In each site the 10 dominated trees were randomly selected. From each trees five samples of the two-year needles were sampled. After sampling, needles were combined to give one composite sample per site. The samples were stored in plastic bags in a freezer (–4 °C) before analysis [21].

2.3. Analytical methods

The concentrations of chlorophyll *a* and chlorophyll *b* in two-year needles were determined spectrophotometrically using a SF–2000 instrument according to follow methodical [22]. Approximately 0.1 g crushed needles samples were soaked in 2 mL dimethyl-sulfoxide and incubated in water bath at 67°C for three hours. The absorbance of samples was measured at 665 nm (chlorophyll *a*) and 649 nm (chlorophyll *b*).

Content of chlorophylls and carotenoids was calculated using the following equations by Wellburn [23]:

$$\mathrm{Cchl}\ a = 12.19 \times \mathrm{A}\ 665 - 3.45 \times \mathrm{A}\ 649 \tag{1}$$

$$\mathrm{Cchl}\ b = 21.99 \times \mathrm{A}\ 649 - 5.32 \times \mathrm{A}\ 665 \tag{2}$$

where A is the absorbance; Cchl *a* is concentration of chlorophyll *a*, mg/mL; Cchl *b* – is concentration of chlorophyll *b*, mg/mL.

Pigment concentration was expressed as mg per g of raw weight using the following equation by Wellburn [23]:

$$\mathrm{PC} = (\mathrm{C} \times \mathrm{V})/(\mathrm{H} \times 1000) \tag{3}$$

where: PC – content of pigments in needles, mg/g of raw weight; C – pigment content in extract, mg/mL; V – volume of extract, mL; H – weight of needles, g.

All determination was done in four replicates for each species.

2.4. Statistical analysis

The results were statistically analysed using a descriptive statistics. The differences between mean values from environmental imputed area and control were tested by a Student's t-test for independent variables at 5% probability level ($p < 0.05$) [24, 25]. Statistical analysis was performed using Microsoft Office Excel 2003.

3. Results and discussion

The territory of Kryvyi Rih Botanical Garden arboretum is characterized by environmentally friendly conditions for spruce species. That is why in control plot, the basic morphometric characteristics included tree height (14.8±0.14 m and 12.1±0.22 m for Norway spruce and Colorado blue spruce, respectively) and diameter at breast height (26.7±0.71 cm and 25.9±0.65 for Norway spruce and Colorado blue spruce, respectively) were typical of mature spruce 30–40-year-old trees and comparable to those reported by many authors [26, 27]. It should also be noted that in the control plot, the vitality of spruce trees was assessed as "healthy": 93.3% and 95.7% for Norway spruce and Colorado blue spruce, respectively (table 1).

According to obtained results, in control site the tree height of spruce species were more and the diameter at breast height of spruce species were large than morphometric characteristics of same age spruce trees from environmental impact areas (table 1). Thus, in low environmental impact area the mean of tree height of Colorado blue spruce was statistical significance lower than the bouground value (by 11.5%). In moderate environmental impact area the means of tree height were lower than control (by 18.2% and 19.1% for Norway spruce and Colorado blue spruce, respectively ($p < 0.05$)). In this area the means of diameter at breast height were statistical significance lower than mean values from bouground area (by 16.3% and 8.1% for Norway spruce and Colorado blue spruce, respectively ($p < 0.05$)). In high environmental

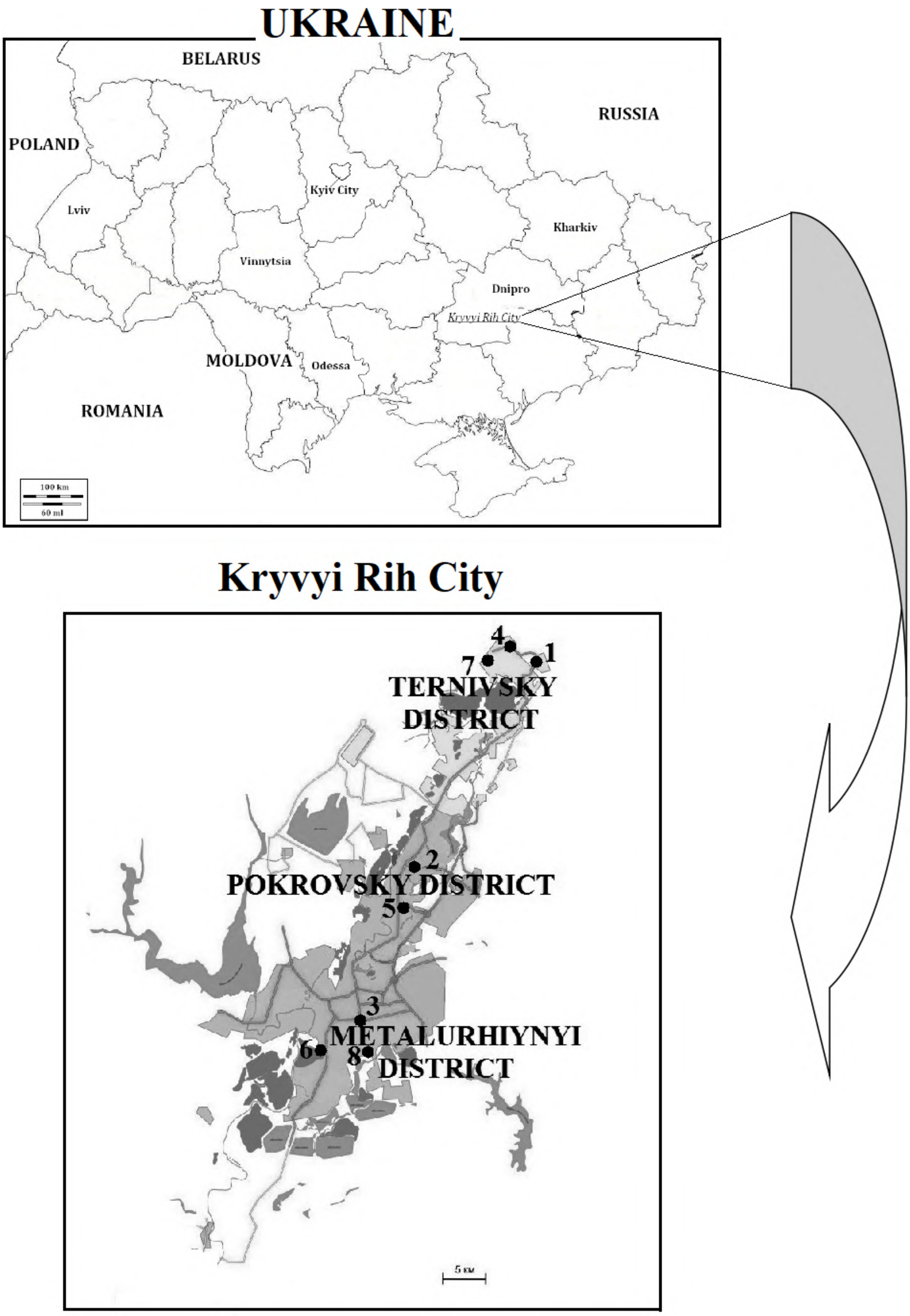

Figure 1. Location of study areas (1 – control sampling site, 2-8 – environmental impact sampling sites).

Table 1. Morphometric characteristics and vitality of spruce species along an environmental gradient in Kryvyi Rih City urban areas, M ± SD.

Environmental impact level	Tree height, m	Diameter at breast height, cm	Vitality,%	Tree height, m	Diameter at breast height, cm	Vitality,%
		Norway spruce (*Picea abies*)			Colorado blue spruce (*Picea pungens var. 'Glauca'*)	
Control	14.8±0.14	26.7±0.71	93.3±2.20	12.1±0.22	25.9±0.65	95.7±1.60
Low	14.0±0.38	25.4±0.32	80.0±1.04*	10.7±0.23*	24.9±0.26	86.3±2.28*
Moderate	12.1±0.37*	25.0±0.34*	67.8±3.85*	9.8±0.35*	24.1±0.42*	73.5±2.98*
High	10.4±0.32*	21.2±0.52*	46.6±3.52*	8.6±0.06*	22.1±0.49*	57.4±0.64*

M – Mean; SD – Standard Deviation. Asterisks indicate that the difference between control and research plots are statistically significant, $p \leq 0.05$.

impact area the means of tree height were lower than the bouground value (by 30.1% and 28.1% for Norway spruce and Colorado blue spruce, respectively ($p < 0.05$)). In this area the means of diameter at breast height were statistical significance lower than control (by 21.6% and 14.9% for Norway spruce and Colorado blue spruce, respectively ($p < 0.05$)).

According to obtained results, in control site the tree height of spruce species were more and the diameter at breast height of spruce species were large than morphometric characteristics of same age spruce trees from environmental impact areas (table 1). Thus, in low environmental impact area the mean of tree height of Colorado blue spruce was statistical significance lower than the bouground value (by 11.5%). In moderate environmental impact area the means of tree height were lower than control (by 18.2% and 19.1% for Norway spruce and Colorado blue spruce, respectively ($p < 0.05$)). In this area the means of diameter at breast height were statistical significance lower than mean values from bouground area (by 16.3% and 8.1% for Norway spruce and Colorado blue spruce, respectively ($p < 0.05$)). In high environmental impact area the means of tree height were lower than the bouground value (by 30.1% and 28.1% for Norway spruce and Colorado blue spruce, respectively ($p < 0.05$)). In this area the means of diameter at breast height were statistical significance lower than control (by 21.6% and 14.9% for Norway spruce and Colorado blue spruce, respectively ($p < 0.05$)).

As demonstrated in table 1, in all environmental impact areas the vitality values of the all spruce species were statistical significance lower than control levels. The vitality values in Norway spruce trees were significantly lower in low environmental impact area by 15-16% ($p < 0.05$), in moderate environmental impact area by 17-18% ($p < 0.05$) and in high environmental impact area by 50-51% ($p < 0.05$). Colorado blue spruce alsow showed differences in vitality values but showed a more smaller amplitude. The means of tree vitality was statistical significance lower than the control value by 9.9%, 23.2% and 40.0% in low, moderate and high environmental impact areas, respectively ($p < 0.05$).

The needles chlorophyll concentration is an important parameter that is regularly measured as an indicator of plant metabolism, plant stress and of plant's current state in urban areas [11, 28–31]. It has been found that maximum contents of chlorophyll *a* in needles of spruce species were in May in control site: 1.04 mg/g of wet weight and 1.24 mg/g of wet weight for Norway spruce and Colorado blue spruce, respectively (figure 2). These values were statistical significance higher than concentration of this pigment in environmental impact areas by 16.3% – 20.6% ($p < 0.05$). The results of our study concur with the findings of previous researches.

The data of many authors in different countries indicated a higher concentrations of chlorophyll a in needles of spruce species in May [6, 32]. This is due to sufficient rainfall and optimal air temperature for the plant development, increasing during the next months.

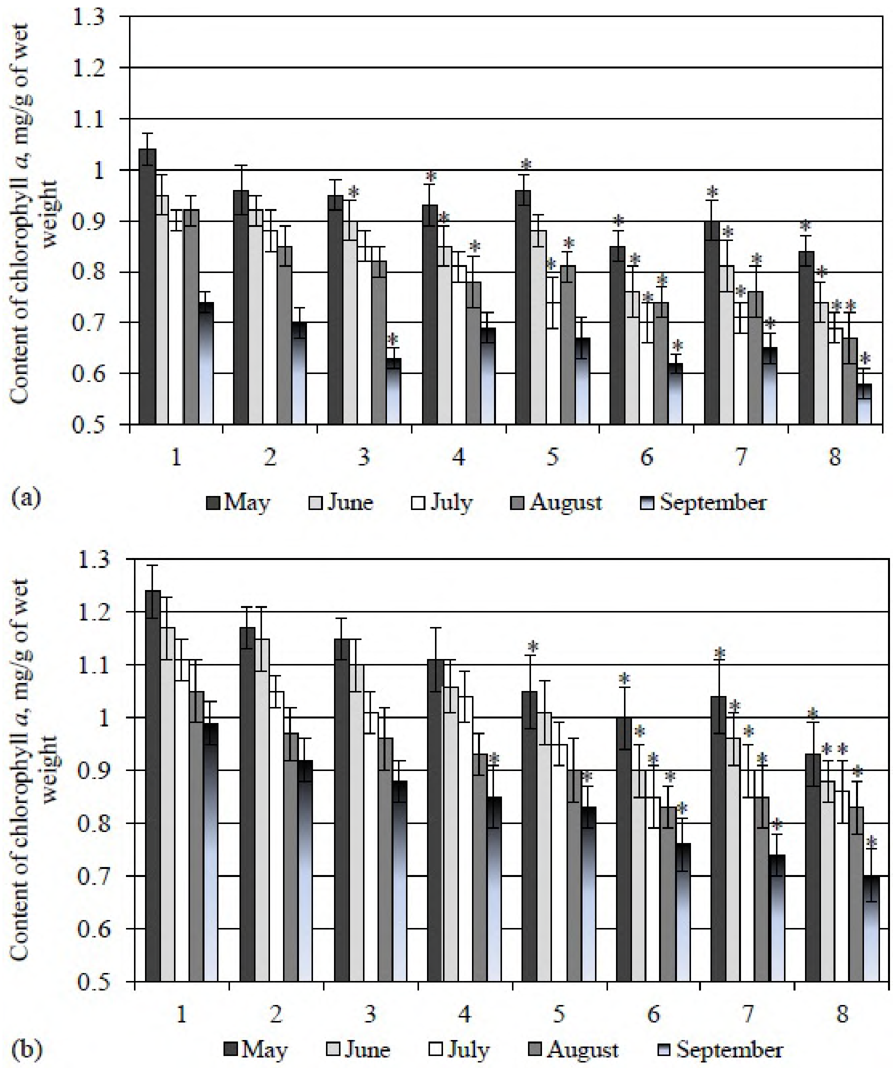

Figure 2. Content of chlorophyll a in needles of spruce species along an environmental gradient in Kryvyi Rih City urban areas, mg/g of wet weight, $n = 5$ (A – Norway spruce (Picea abies), B – Colorado blue spruce (Picea pungens var. 'Glauca'). 1 – control site, 2-8 – environmental impact sites. Asterisks indicate that the difference between control and research sites are statistically significant, $p \leq 0.05$).

The lowest chlorophyll a content in needles of spruce species were found in September in high environmental impact area: 0.58 mg/g of wet weight and 0.70 mg/g of wet weight for Norway spruce and Colorado blue spruce, respectively. These values were lower than control by 21.6% and 29.3% ($p < 0.05$). For both species, we observed a general tendency to reduce this pigment concentration during summer and autumn, especially in September, as this period was characterized by low rainfall and air drought. In the course of five-month studies, was found a significant decline in the chlorophyll a content in needles of spruce species along an environmental gradient. But in all environmental impact areas the content of this pigment in the needles of Colorado blue spruce was a relative stability and higher than in the needles of Norway spruce. We hypothesize that Norway spruce is more sensitive to environmental impact than Colorado blue spruce.

The result of our investigation clearly indicated that minimal contents of chlorophyll b in needles were found in September in high environmental impact area (near cast iron smelting and steel smelting plants). At this site concentration of chlorophyll b was 0.29 mg/g of wet weight in needles of Norway spruce and was and 0.33 mg/g of wet weight in needles of Colorado blue spruce. These values were lower than control by 14.7% and 21.4%, respectively ($p < 0.05$).

During five months of our investigations, there was a significant decrease in the value of chlorophyll b concentration in the needles of both spruce species along an environmental gradient in Kryvyi Rih City urban areas. We imply that this phenomenon is determined by distance from urban roads, from ore mining and processing enterprises and from metallurgical combine.

It is known from earlier publications that environmental pollution decreased the content of chlorophyll b in needles more than the content of chlorophyll a in needles [11,32]. It may reduce the activity of the photosynthetic apparatus and disrupt the plants metabolism. However, other researchers reported that chlorophyll a was to be less stable than chlorophyll b in the pigment complex of conifers in urban areas [33, 34]. In our research, the second variant of the dynamic changes in pigment complex of needles was confirmed: along an environmental gradient in Kryvyi Rih City urban areas more significantly decreases the content of chlorophyll a than content of chlorophyll b.

Still remain controversial the data about of the photosynthetic apparatus stability in coniferous plants under environmental effects. Some authors [35] were noted that Norway spruce and Colorado blue spruce had the same inhibition effects of the pigment complex functioning under the stress influence of the air pollution. But according to results of the our research Colorado blue spruce had a better adaptive balance of pigment content than Norway spruce.

Many authors [6,10,11,32,36,37] reported that the morphometric characteristics, vitality and intra-annual dynamics of chlorophyll content in needles of spruce species determined by climatic conditions and environmental impact level. According to our results, the maximum decrease of values of morphometric characteristics, vitality and chlorophyll content were wound in the southern part of the Kryvyi Rih City near largest in Ukraine processing, cast iron smelting and steel smelting enterprise. Finally, our results are agree with several numerous studies and key sciences publications. The obtained results of this study help to provide important information on understanding how trees of spruce species can affecting on urban ecology and urban sustainable development by temperature reduction, by reduce heat stress, by carbon storage and by promoting biodiversity. Besides, they may serve as reference levels for future studies in other urban areas at similar sites all over the world.

As in previous case, the maximum contents of chlorophyll b in needles of spruce species were in May in control site: 0.41 mg/g of wet weight and 0.50 mg/g of wet weight for Norway spruce and Colorado blue spruce, respectively (figure 3). These values were statistical significance higher than concentration of this pigment in environmental impact areas by 9.8% – 18.0% ($p < 0.05$).

4. Conclusions

In the present study, the large range of morphometric characteristics, vitality and of chlorophyll content in needles of Norway spruce and Colorado blue spruce were observed. In control plot, the tree height, diameter at breast height, chlorophyll a content and chlorophyll b content were typical of mature spruce 30–40-year-old trees. Based on the obtained results, it can be concluded that spruce species is affected by environmental impact. In Kryvyi Rih City urban areas the ecological stress along an environmental gradient decreased the values of growth, vitalyty and photosynthetic activity of the trees by 15-50%. Our study demonstrated that Colorado blue

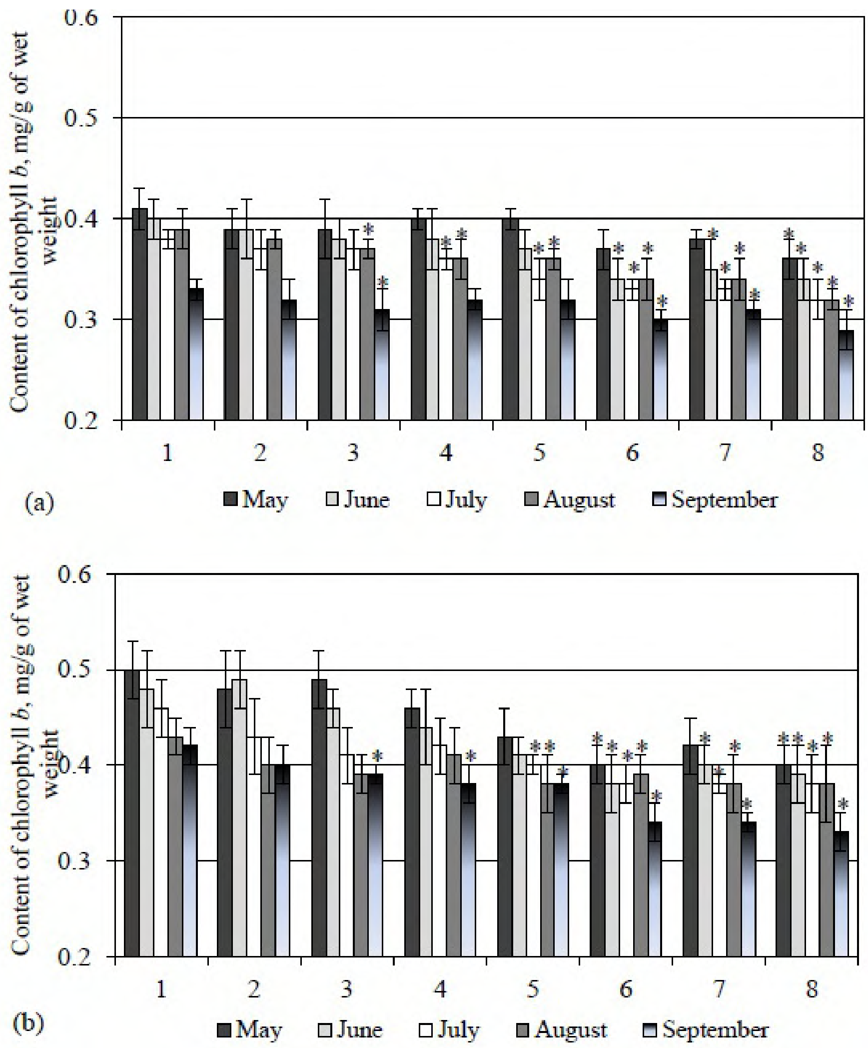

Figure 3. Content of chlorophyll b in needles of spruce species along an environmental gradient in Kryvyi Rih City urban areas, mg/g of wet weight, $n = 5$ (A – Norway spruce (Picea abies), B – Colorado blue spruce (Picea pungens var. 'Glauca'). 1 – control site, 2-8 – environmental impact sites. Asterisks indicate that the difference between control and research sites are statistically significant, $p \leq 0.05$).

spruce trees exhibit greater ecological tolerance and ecological adaptations than Norway spruce trees. Colorado blue spruce is less sensitive to environmental impact and have a better adaptive balance of pigment content than Norway spruce. Our results confirm that from a sustainable development of the urbane areas perspective it is necessary to using the Colorado blue spruce for green planting.

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References

[1] Liu Y, Yang X, Tan J and Li M 2023 *Environmental Pollution* **327** 121535 ISSN 02697491 URL https://doi.org/10.1016/j.envpol.2023.121535
[2] Savosko V, Lykholat Y, Komarova I and Yevtushenko E 2022 *Baltic Forestry* **28** URL https://doi.org/10.46490/BF631
[3] Russo A, Chan W T and Cirella G T 2021 *Land* **10**(8) 788 ISSN 2073-445X URL https://doi.org/10.3390/land10080788
[4] Linden J, Gustafsson M, Uddling J, Watne A and Pleijel H 2023 *Urban Forestry and Urban Greening* **81** 127843 ISSN 16188667 URL https://doi.org/10.1016/j.ufug.2023.127843
[5] Nowak D, Hirabayashi S, Bodine A and Greenfield E 2014 *Environmental Pollution* **193** 119–129 URL https://doi.org/10.1016/j.envpol.2014.05.028
[6] Bessonova V P and Ponomaryova O A 2017 *Biosystems Diversity* **25** 96–101 URL https://doi.org/10.15421/011714
[7] Hirabayashi S 2021 *Trees Forests and People* **4** 100078 ISSN 26667193 URL https://doi.org/10.1016/j.tfp.2021.100078
[8] Jones B A 2021 *Forest Policy and Economics* **125** 102408 ISSN 13899341 URL https://doi.org/10.1016/j.forpol.2021.102408
[9] Wolf K L, Lam S T, McKeen J K, Richardson G R, van den Bosch M and Bardekjian A C 2020 *International journal of environmental research and public health* **17** 4371 URL https://doi.org/10.3390/ijerph17124371
[10] Fedorchak E 2020 *Ekologia (Bratislava)* **39** 1–15 URL https://doi.org/10.2478/eko-2020-0001
[11] Sciukaite A, Loziene K, Labokas J and Jurkoniene S 2022 *Industrial Crops and Products* **182** 114919 ISSN 09266690 URL https://doi.org/10.1016/j.indcrop.2022.114919
[12] Eyster H N and Beckage B 2022 *Atmosphere* **13** 830 URL https://doi.org/10.3390/atmos13050830
[13] Nikolic M B, Stefanovic A M, Veselinovic M M, Milanovic D S, Mladenovic D K, Mitrovic Z S, Eremija M S and Rakonjac B L J 2019 *Applied Ecology and Environmental Research* **17** 2831–2848 URL https://doi.org/10.15666/aeer/1702_28312848
[14] Goudarzi G, Hopke P and Yazdani M 2021 *Chemosphere* **283** 131285 ISSN 00456535 URL https://doi.org/10.1016/j.chemosphere.2021.131285
[15] Yu B, Lu X, Wang L, Liang T, Fan X, Yang Y, Lei K, Zuo L, Fan P, Bolan N and Rinklebe J 2023 *Environmental Pollution* **327** 121523 ISSN 02697491 URL https://doi.org/10.1016/j.envpol.2023.121523
[16] Sgrigna C, Baldacchini S, Dreveck Z and Cheng C 2020 *Science of The Total Environment* **718** 137310 ISSN 00489697 URL https://doi.org/10.1016/j.scitotenv.2020.137310
[17] Chypyliak T F and Zubrovska O M 2022 *Hacquetia* **21** 223–233 URL https://doi.org/10.2478/hacq-2021-0025
[18] Schaefer M 2022 *Urban Ecosystems* **25** 1805–1824 URL https://doi.org/10.1007/s11252-022-01268-x
[19] West P 2009 *Tree and Forest Measurement* (Berlin, Heidelberg: Springer-Verlag) URL https://doi.org/10.1007/978-3-540-95966-3
[20] Yarmishko V T 2002 *Diagnosis of damage and assessment of the vital state of trees and forest stands under conditions of industrial atmospheric pollution. Methods for studying forest communities* (St. Petersburg: NIIkhimii St. Petersburg State University)
[21] Moorthy I, Miller J and Noland T 2008 *Remote Sensing of Environment* **112** 2824–2838 URL https://doi.org/10.1016/j.rse.2008.01.013
[22] Bessonova V P 2006 *Practical work on plant physiology* (Dnepropetrovsk)
[23] Wellburn A R 1994 *Journal of Plant Physiology* **144** 307–313 URL https://doi.org/10.1016/S0176-1617(11)81192-2
[24] McDonald J 2014 (University of Delaware, USA: Sparky house publishing) URL https://www.biostathandbook.com/
[25] Bulmer M G 1979 *Principles of statistics* (New York, USA: Dover Publications Inc) URL https://www.worldcat.org/title/Principlesofstatistics/oclc/802571746
[26] Sharma R P, Vacek Z, Vacek S, Jansa V and Kučera M 2017 *Journal of Forest Science* **63** 227–238 URL https://doi.org/10.3390/rs10081202
[27] Mehtätalo L 2004 *Canadian Journal of Forest Research* **34** 131–140 URL https://doi.org/10.1139/x03-207
[28] Tomaskova I, Pastierovic F, Krejzkova A, Cepl J and Hradecky J 2021 *Acta Physiologiae Plantarum* **43** 1–6 URL https://doi.org/10.1007/s11738-020-03190-1

[29] Annala L, Honkavaara E, Tuominen S and Pölönen I 2020 *Remote Sensing* **12** 283 URL https://doi.org/10.3390/rs12020283
[30] Kovac D, Veselovska P, Klem K, Vecerova K, Ac A, Penuelas J and Urban O 2018 *Remote Sensing* **10** 1202 URL https://doi.org/10.3390/rs10081202
[31] Hoeppner J M, Skidmore A K, Darvishzadeh R, Heurich M, Chang H C and Gara T W 2020 *Remote sensing* **12** 3573 URL https://doi.org/10.3390/rs12213573
[32] Lepedus H, Cesar V and Suver M 2003 *Acta Botanica Croatica* **62** 27–35 URL https://hrcak.srce.hr/file/5897
[33] Bukharina I L, Vedernikova K E and Pashkova A S 2016 *Forest Studies* **2** 96–106 URL https://doi.org/10.1134/S1995425516070027
[34] Huemmrich K F, Campbell P, Sackett S, Unger S anf May J, Tweedie C and Middleton E 2022 *Environmental Research Communications* **4** 035001 URL https://doi.org/10.1088/2515-7620/ac5365
[35] Soukupova J, Rock B N and Albrechtova J 2001 *New Phytologist* **150** 133–145 URL https://doi.org/10.1046/j.1469-8137.2001.00066.x
[36] Lučinskaitė I, Laužikė K, Žiauka J, Baliuckas V, Čėsna V and Sirgedaitė-Šėžienė V 2021 *Wood Science and Technology* **55** 1221–1235 ISSN 00437719 URL https://doi.org/10.1007/s00226-021-01322-5
[37] Böhner H, Rose L, von Sengbusch P and Scherer-Lorenzen M 2019 *Mires and Peat* **24** 1–13 URL https://doi.org/10.19189/MaP.2018.DW.335

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Satellite-based technology assessing Ukraine's ecology under the war

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Satellite-based technology assessing Ukraine's ecology under the war

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Abstract. The Donbas is a region dominated by heavy industry, particularly coal mining, chemical processing sites and metallurgy. Intensive mining and steel smelting led to substantial environmental damage before the armed conflict. The fighting in eastern Ukraine has exacerbated an already fragile ecological situation, introducing a range of new risks – of stray munitions hitting extensive chemical and industrial facilities or interconnected mines being flooded and poisoning the water throughout the region. Besides, one of the main hazards is flooding territories associated with closing coal mines. Assessment impacts of uncontrolled mine flooding and towns and villages and associated hazardous processes of surface and groundwater contamination, surface subsidence and dangerous deformations of residential and industrial buildings and other facilities carried out the remote sensing and geological data.

1. Introduction

Nowadays, the negative anthropogenic impact on the environment is felt especially acutely and has acquired a global character. This is because the effect on nature was previously insignificant, but now it predominates, and new factors constantly appear. Damage caused to natural components leads to negative consequences and reflects the reverse reaction of this impact (adverse for society). Such dangerous environmental changes (primarily of anthropogenic nature) spreads over several hundred thousand square kilometres of the territory of Ukraine.

Recently, the environmental situation in the Donbas has been sharply aggravation caused by the decommissioning of mines and their transition to a new ecological state. We should note that the environmental situation in the Donetsk and Luhansk regions has significantly worsened in recent years and became the theatre of military conflict with active hostilities in 2014-2023 and was partially under the power of the occupation forces, acquiring signs of an ecological disaster. There are 220 coal mines on the territory of the Donetsk coal basin, 97 of which are in operation, 14 are in drainage mode, 39 are in the process of flooding, and 70 are at the liquidation stage. In addition, a total of 2 mines were deregistered due to the completion of liquidation works [1].

Stopping the operation of drainage and ventilation equipment causes the accumulation of water and methane in the mines. The rise in the level of underground water significantly increases the impact of negative artificial factors and leads to the following: flooding of significant areas of pollution of underground and surface sources of drinking water, rivers and reservoirs; a critical reduction in the strength and bearing capacity of mining rocks and soils within the limits of the influence of mining; expansion of subsidence zones of the massif with the possibility of violations of surface structures; increasing seismic hazard; the formation of unpredicted explosive areas due to changes in methane migration routes. Critical conditions have been created for solving the mentioned problems in almost the entire region of Donbas.

The actual rates of filling mines with water are much higher than expected, which were calculated based on natural filtration coefficients of the mining massif and other multiparametric factors [2]. Hence, the need for more accurate data on the environment's basic parameters and unforeseen problems arise after the closure of mines. In addition, the situation is complicated by the need for more reliable data on hydrogeological connections between mines.

The remote sensing technique's efficiency, cost-effectiveness and productivity make it reasonable to use them in solving complex geological hydrogeological, geophysical and environmental problems related to regional geo-ecological security. In this study, ecological issues associated with the flooding of mine waters due to the closure of coal mines are solved (in the example of the territory of the Main Anticline of Donbas).

2. Analysis of the state of the study of the existing native experience regarding the threats of flooding associated with the closure of coal mines

Numerous works by Ukrainian scientists give environmental monitoring and coverage of the consequences of the closure of mines. As evidenced by studies of Rudko and Yakovlev [3, 4], Dovgiy et al [5, 6], Dovgyi and Korzhnev [7], Shybetskyi et al [8], Panova et al [9], Goshovskyi and Zurian [10], Trofymchuk et al [11, 12], Anpilova et al [13], Dolin et al [14], Lyuta and Sanina [15]. During the full-scale development of the mining area, the geological environment becomes the primary "depot" of the majority of man-made emissions and mechanical, physical and chemical effects on the components of the environment (ground atmosphere and surface hydrosphere, soils, the upper zone of the lithosphere, etc.).

The wet method of closing mines is most often used today in Ukraine – the damp process conserves 90 percents of mines. However, many environmental problems have arisen due to its use since the man-made load on the geological environment; the hydrosphere increases significantly when the mining works are flooded. In addition, large areas of coal-bearing rocks opened by mining and a sharp increase in their permeability due to the man-made fracturing of rocks led to the active influence of mines on the hydrogeological conditions of the surrounding territories [16].

The consequences of mine liquidation have yet to be thoroughly studied, so it isn't easy to choose the final, most rational method of mine liquidation from the point of view of ecology and economic market relations. Nevertheless, the processes of man-made influence must be monitored and analyzed in detail to ensure the minimum negative impact of liquidated mines on the environment. Therefore, it is necessary to carry out routine monitoring observations using ecological methods and the application of remote sensing data. This makes it possible to carry out work in the monitoring mode, to investigate two typical signs of the flooding process – subsidence of the surface and an increase in the area of soil moistening and the release of underground water to the surface. Unfortunately, such studies are still rare in Ukraine. In particular, modelling the potential development of flooding was carried out, taking into account the zones of propagation of large-amplitude movements, which are given by Ulytsky and Boyko [17]. Therefore, the methods of representation of the remote sensing data and the results of the processing are tools for anticipatory forecasting of changes in the hydrogeological situation within the territories of the distribution of mines flooded and liquidated.

3. Geological structure of the region of the Main Anticline of Donbass

The main anticline is located in the axial part of the Donbas and is the most significant linear fold of the Donetsk Basin. The anticline is confined to the longitudinal Central-Donetsk deep-seated fault, common to Donbas and the Dnipro-Donetsk depression (figures 1 and 2).

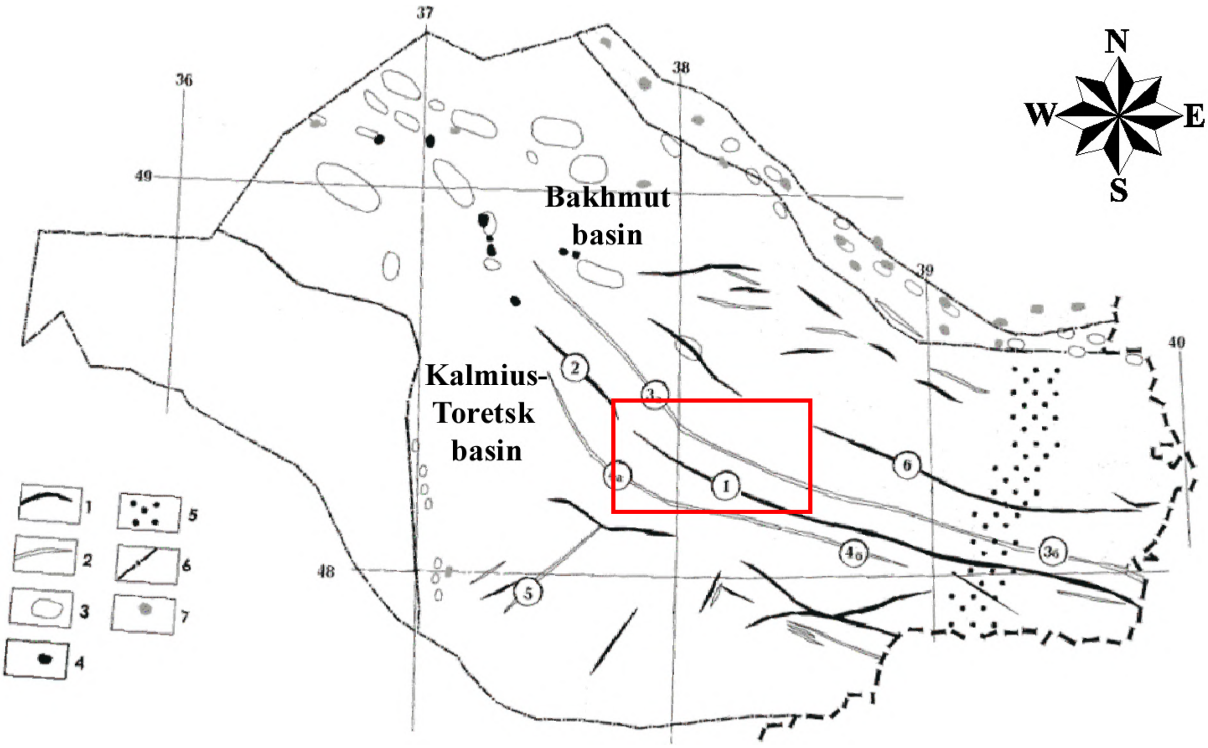

Figure 1. Scheme of plicative structures of Donbas according to [18]. Legend: 1 – anticlines (1 – Main, 2 – Druzhkivsko-Kostiantynivska, 6 – Northern), 2 – synclines (3 – Main: 3a – Bokovo-Khrustalska, 3b – Dovzhanska-Sadkinska, 4 – South: 4a – Chistyakovo-Snizhnyanska, 4b – Shakhtynsko-Nesvitaevska, 5 – Vovchanska), 3 – brachyanticlines, 4 – salt stem, 5 – Stepanov shaft (transverse Rovenkiv uplift), 6 – borders of the region, 7 – gas deposits. The red rectangle is the research region.

The main anticline is a linear fold that extends in a straight line along the azimuth of approximately SW 3000 and dips undulipodia to the northwest at an angle of 3-50. Anticlinal folds of the second order are established within its boundaries. The formation of ore bodies, including the Mykytivske mercury deposited, is connected with these structures.

Rocks that make up the fold flanks lie symmetrically with steep dips (50-700). The axial plane of the anticline is vertical or dips steeply to the northeast. Immovables complicate the structure of the Main anticline.

The oldest rocks are exposed in the axial part of the anticline and belong to the Serpukhovian stage of the Lower Carboniferous (geological suite C51), about 400 m thick. The sediments are represented mainly by shale and are characterized by extremely low carbon content.

Deposits of the middle part of the coal system are the most widely distributed in the research region. They are divided into seven suites belonging to the Bashkirian and Moscovian Stages. According to the lithological composition of the rocks, they are typical for the Donetsk basin. This alternation of marine and continental deposits, clay and sandy shales, sandstones and subordinate layers of limestone and coal. The thickness of the Middle Carboniferous deposits increases from 2525 m in the northwest to 4885 m in the southeast.

The middle section is the main coal-bearing part of the Donetsk Carboniferous and has about 66 coal seams, a large amount of which reaches the working thickness.

The lower layers of the Middle Carboniferous rocks consistently cover the sediments of the upper part of the coal system. They are represented by a rhythmic layering of sand-clay rocks,

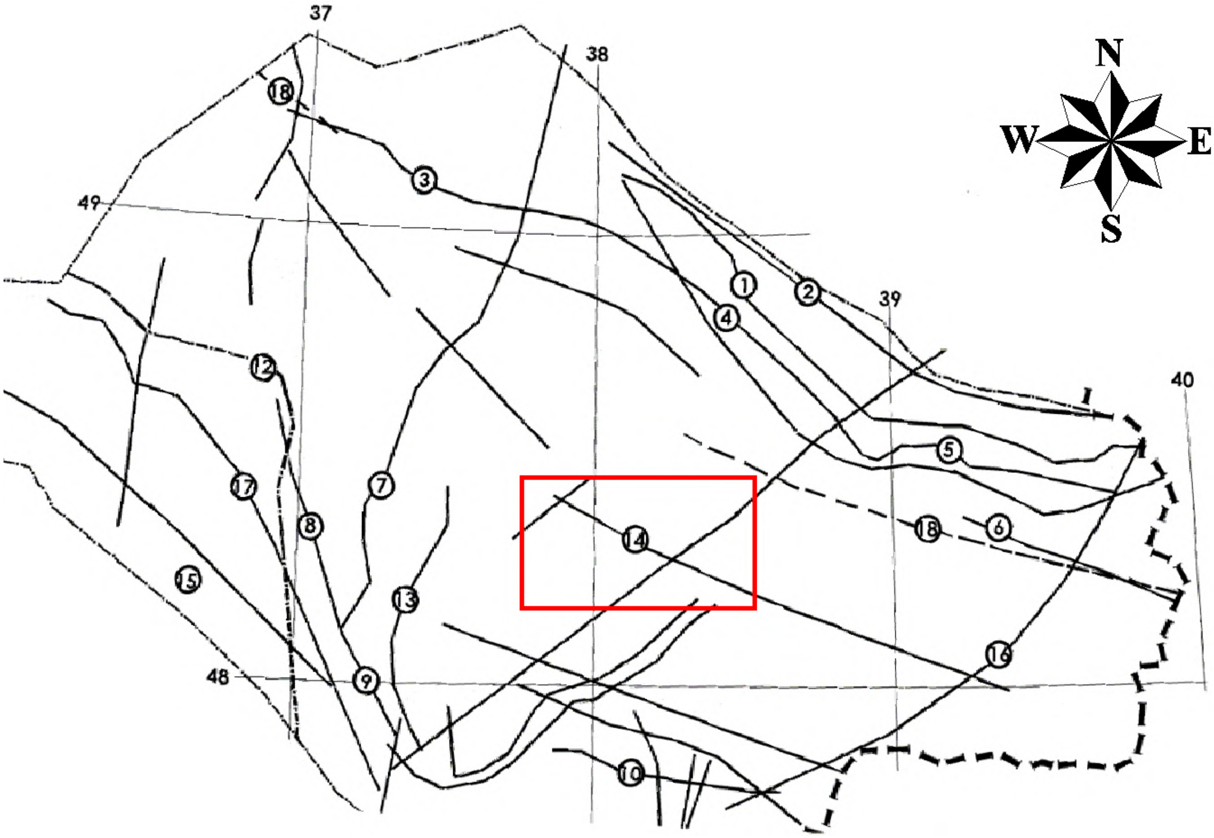

Figure 2. Figure 2 – Main faults of Donbas according to [18]. Legend: 1 – North Donetsk thrust, 2 – Krasnoretsky thrust, 3 – Sviatohirsky thrust, 4 – Maryiv thrust, 5 – Almaznyy thrust, 6 – Krasnodon thrust, 7 – Central thrust, 8 – Kotlyn thrust, 9 – Yalinsky thrust, 10 – Kuteinikovsky skid, 11 – Southern Donbas fault, 12 – Central-Priazov fault, 13 – Selydiv thrust, 14 – Main anticline fault, 15 – Southern Donbas fault, 16 – Yelanchyk-Rovenkiv fault, 17 – Kryvorizko-Pavlivskii fault, 18 – the presumed northeastern marginal fault of the Riphean graben. The red rectangle is the research region.

limestones and coal. However, the frequency and amplitude of oscillations are significantly reduced compared to the underlying layers of rocks, and the section becomes more uniform. Deposits are widely distributed to the southwest and northeast of the axis of the Main anticline within the synclines.

Sediments of the Mesozoic-Cainozoic age are spread outside the Main anticline on the territory of adjacent syncline structures.

The territory where the Main anticline is located belongs to the open Donbas, rising at an average rate of 2.5-3.8 mm/year.

According to the data of deep seismic sounding (DSS), a rigid plate of the Precambrian folded basement is reliably fixed under the open Donbas. Thus, the area has a two-tiered structure typical for a platform with imitation of basement faults in the form of tense anticlinal folds and rigid blocks – in the state of fields of relatively calm deposits of Paleozoic rocks with sustained thickness and stable composition. The change in the structure, composition and metamorphism of rocks does not occur gradually or imperceptibly but rather abruptly within areas that are sufficiently narrow and strictly fixed for the entire section. The formed fault-block structure of the territory significantly impacted the development of a wide variety of processes – geodynamic, seismic, filtration, ore and gas formation [19–21].

The formation of the Main anticline and the surrounding area, according to Gintov et al [22], took place in 10 stages [23]. First, we established that the direction of the tension axis was longitudinal relative to the anticline, and the sub-vertical orientation of the compression axis characterized the Kimmerian stress field. The voltage field has a pulsating character. At the same time, there was a change in the indexing of the tension axis with the intermediate axis of the stress field. The reset character of the deformations in stretching conditions along one axis prevailed [23, 24].

Within the Main anticline, the coal-bearing of the southern flank of the anticline is higher than that of the northern flank. Consequently, coking grades of coal have been developed in most of the regions of the district. The degree of coalification in the section increases from the upper to lower horizons. It is represented most clearly on the northern flank and less on the southern side.

The water-bearing capacity of coal deposits is generally low. Inflows into mining operations for individual coal seams are at most 100 m^3/hour. With depth, the fracturing and water-bearing capacity of coal deposits decreases significantly. At a depth of 400-500 m and more, the deposits of the coal system are practically waterless, except for regions of local irrigation within the zones of tectonic disturbances.

The main aquifers are adapted to limestones and sandstones of the coal system and, within the weathering zones, water-bearing and fractured shales. Limestones are the most fractured rocks. Sources with a flow rate of up to 11.0 l/sec are adapted to their exits to the daylight surface. The flow rates of springs fed by sandstone waters are usually one l/sec. But the total costs for sandstone springs are generally much higher than for limestone springs because sandstones are much thicker than limestone.

Among the many numerous tectonic disturbances in the area, especially discharges, are characterized by increased water capacity.

Thrusts, as a rule, could be better watered. Water inflows from tectonic zones quickly decrease over time, and after a few months, they stop altogether. Coal aquifers are mainly fed by atmospheric precipitation, which causes significant fluctuations in inflows to mines by two or more times throughout the year. In addition, a hydrographic network and numerous mining operations drain coal aquifers. The waters of coal deposits, regardless of water-bearing rocks (limestones or sandstones), are characterized by high mineralization and hardness and therefore are usually unsuitable for drinking and technical water supply. Mine waters have an even worse quality characteristic – the content of dry residue in the water reaches 5000 mg/l and more, and the hardness is more than 100 nem. degree. Despite the poor quality of water from coal deposits, the water is partially used for drinking and technical water supply, and in agriculture, it is used for watering livestock.

4. Formation of the fractographic base, selection of the necessary satellite images

The database of input materials was formed using the Remote Sensing Software Erdas Imagine, which allowed them to be analyzed and compared. As a coordinate system, a rectangular coordinate system was chosen – UTM / WGS 84 / zone 37. The choice of this coordinate system is due to the zone in which the research area is located (zone 37), and the selection of the UTM / WGS 84 system is because the data of remote sensing of the Earth have precisely this coordinate system. Geometric correction of the input data was carried out in the space image processing program Erdas Imagine using the Geometric Correction module.

The study used a digital terrain model from the Shuttle satellite to the study area. Also, we took satellite images from the Landsat 8 satellite on October 9, 2020, for the study area (figure 3).

Using the Erdas Imagine software, we made a mosaic of topographic maps with a spatial

Figure 3. Fragment of the image from the Landsat 8 satellite on October 09, 2020, a combination of channels 7 (SWIR2) – 5 (NIR) – 4 (RED), the spatial resolution of 30 m. In addition, topographic maps on a scale of 1: 100,000 were used for the territory of the nomenclature study (M37 – 124, 125, 126, 136, 137, 138).

resolution of 17 m. A mosaic of geological maps on a scale of 1: 200,000 was made for the study area (figure 4).

5. Results of the assessment of the possibility of establishing flooding of territories based on remote sensing data

Mainly we gave attention to the problem of flooding the territory of Donbas to establish the depth of underground water, the places of its exit to the surface, the flow rate and composition of water, the impact on the environment, etc. But we needed more than the available information for a reliable mapping of the areas of flooding of the daylight surface, which was crucial in solving the issues of the ecology of the surrounding territory. All the more so, since we did not carry out the work in the monitoring mode, all the researchers pointed out the need for such work. The interferometry method based on remote sensing data helped to partly solve this issue [17]. These materials made it possible to establish the area of flooding of the daytime surface based on the assessment of the subsidence of the Earth's surface, which accompanies the flooding process. Using space images allows for monitoring the development of the flooding process over time. But the proposed approach does not record the presence of water on the surface or does not allow the estimation of soil moisture. The presence of water or increased soil moisture directly reflects the development of the process of flooding the territory.

One effective method of determining the daytime surface's humidity based on remote sensing data is using various water indices. Water indices are designed to assess the presence of moisture in vegetation or open ground. The presence of moisture in vegetation directly indicates its condition: a high moisture level characterizes healthy vegetation characterized by good growth. The humidity of the open ground is directly relevant to our research, while the moisture of the

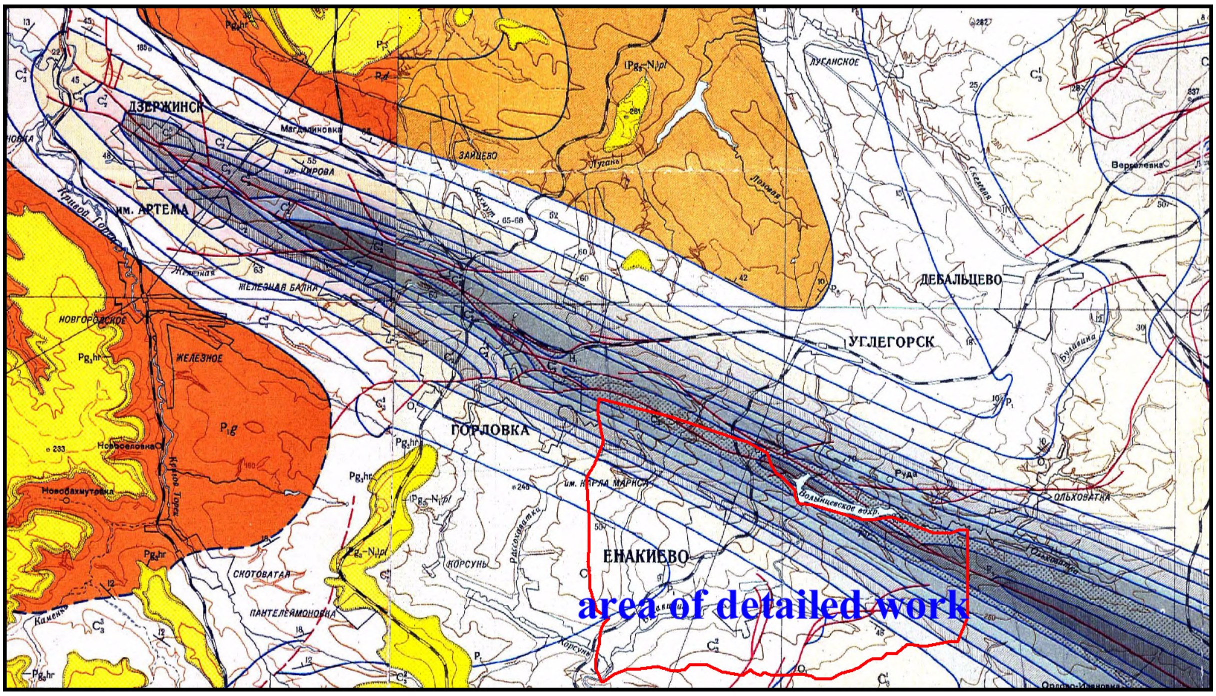

Figure 4. Fragment of a mosaic of geological maps of scale 1: 200,000 nomenclatures (M37 – 32, 33 [19, 20]) for the study area, the spatial resolution of 10 m.

vegetation cover is an indirect indicator of soil moisture. Therefore, we hope the soil moisture indicator will be more informative than the vegetation cover moisture [25, 26].

To calculate humidity indices, values of spectral brightness in the near, medium and infrared ranges are most often used – in the ranges where the radiation is most intensively absorbed by water. These ranges are most sensitive to moisture in vegetation and ground cover. In this study, the five most widely used humidity indices were used: DSWI (Disease water stress index) [27]; NDII (Normalized Difference Infrared Index) [28]; SR-SWIR (Simple Ratio SWIR) [29]; RDI (Ratio Drought Index) [30, 31]; NWI (Normalized Water Index) [32]. The calculation of these indices was carried out using materials from the Landsat-8 satellite.

To assess the possibilities of using the indicated moisture indices for the study of flooding of the territory of Donbas, a mapping scheme (figure 5) of the potential development of subsurface flooding, which accompanies the flooding of mines, taking into account the propagation zones of large-amplitude movements and numerical modelling of geofiltration, was used [17].

According to the data of the mapping scheme, we selected two areas with depths of underground water levels of 0-3 m (flooded "wet" regions) and more than 10 m from the daytime surface ("dry" regions). The values of the five specified humidity indices were calculated for these areas. Separately, the values of the moisture indices were calculated within the areas of "wet" and "dry" areas covered with woody vegetation and open grounds. The comparison of two distributions of values was carried out using the λ criterion (Kolmogorov-Smirnov) [33].

The maximum values of the λ criterion (table 1) were calculated for dry and flooded areas, and we made the ranking of humidity indices.

The analysis of the obtained results proved that statistically, all the areas that were compared using all five moisture indices differ with reliability higher than 0.99. This allows us to state that we can use multiple satellite imagery to establish flooded areas covered with woody vegetation and open ground. The values of the lambda criterion for multiple and areas with open ground

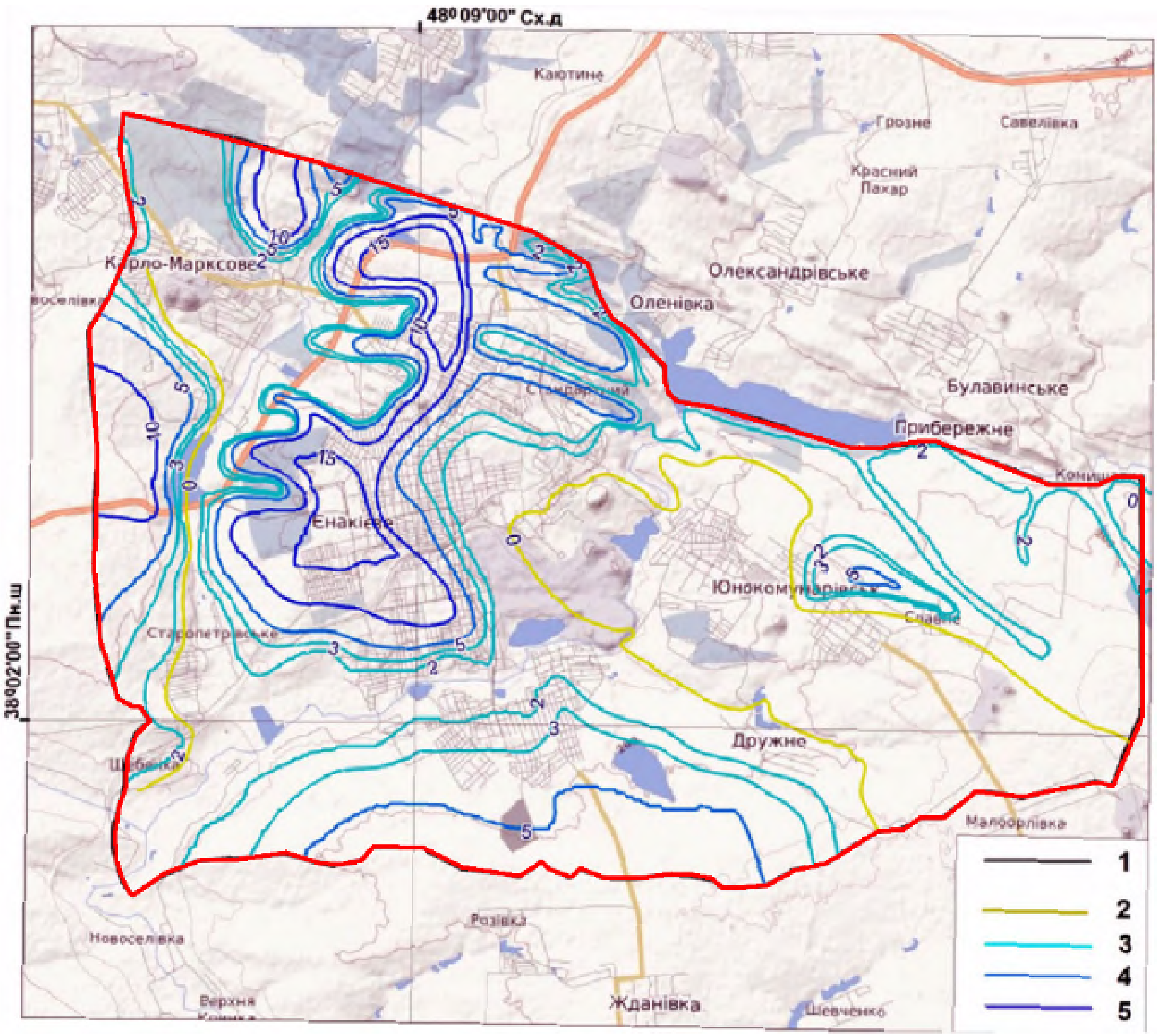

Figure 5. Map-scheme of predicted depths of underground water levels, obtained on the basis of numerical modeling of geofiltration according to [17]. Legend: 1 – catchment area and geofiltration model area; 2–5 – depth of underground water levels, m: 2 – about 0 m; 3 – 1–3 m; 4 – 5–10 m; 5 – more than 10 m.

Table 1. Maximum values of the λ criterion on dry and flooded areas covered with woody vegetation and areas with open ground at different moisture indices.

Area covered with woody vegetation		Areas with open ground	
SW-SWIR	12.3	SW-SWIR	22.1
NWI	5.7	DSWI	21.6
NDII	3.9	NDII	20.9
RDI	3.8	DI	20.9
DSWI	2.4	NWI	9.2

differ significantly from each other (table 1). Areas with dry and flooded soils disagree much more strongly than woody vegetation in arid and flooded areas.

The SR-SWIR index will be the most informative among the five studied moisture indices for areas covered with woody vegetation and open ground. The informativeness of other indexes for the territory covered with woody vegetation will be of the same order, much less than the value of the SR-SWIR index. In the region with open ground, all indices are characterized by relative values of informativeness, and only the NWI index is characterized by significantly lower informativeness.

6. Conclusion

Assessing flooding of the territory, we proposed to use known humidity indices, which are established based on multiple satellite imagery. The analysis of the possibilities of using five moisture indices – DSWI, NDII, SR-SWIR, RDI, and NWI proved that we could use all of them to assess the flooding of territories. Comparing the distributions of the values of the specified indices within dry areas where the depth of groundwater is more profound than 10 m and flooded areas where the depth of groundwater is 0-3 m was performed using the well-known statistical λ criterion (Kolmogorov-Smirnov). As a result of the comparison, it was established that all five water indices could be used to select flooded areas. The ranking of humidification indices according to their capabilities, which was based on the analysis of the values of the λ criterion, showed that the SR-SWIR index is characterized by the most significant capabilities, both for areas covered with woody vegetation and for areas with open ground.

Therefore, the possibility of using multi-zone space images to assess the flooding of the territory of Donbas due to the mass closure of coal mines through the so-called "wet conservation" has been established.

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References

[1] 2021 The environment of Donbass: an invisible front. Ecological consequences of the war in the Eastern Ukraine in the context of the international humanitarian law in the practical terms Report Truth Hounds URL https://truth-hounds.org/wp-content/uploads/2021/06/donbas-ecology-report-2021-truth-hounds.pdf

[2] Yakovlev Y O 2017 *Mineral resources of Ukraine* (3) 34–39 URL https://mru-journal.com.ua/index.php/mru/article/view/219

[3] Rudko H I and Yakovlev Y O 2018 *Mineral resources of Ukraine* (2) 43–50 URL https://doi.org/10.31996/mru.2018.2.43-50

[4] Rudko H I and Yakovlev Y O 2020 *Mineral resources of Ukraine* (3) 37–44 URL https://doi.org/10.31996/mru.2020.3.37-44

[5] Dovgiy S O, Ivanchenko V, Korzhnev M M, Kurilo M M, Trofymchuk O M and Yakovlev E O 2013 *Criteria of ecological and geological-economic assessment and mineralogy of waste from the mining and metallurgical complex of Kryvbas* (Kyiv: Nika-Center)

[6] Dovgyi S O, Korzhnev M N, Trofymchuk O M, Kurylo M M, Yakovliev Y O, Myrontsov M L, Anpilova Y S, Virshylo I V, Kosharna S K, Sukhina E N and Malkova Y O 2022 *Principles of environmental policy formation in the mineral resource complex of Ukraine in modern conditions* (Kyiv: Nika-Center)

[7] Dovgyi S O and Korzhnev M M 2017 *Geological structure and modern geological, economic and ecological conditions of iron ores mining and processing in the Kryvorizska-Kremenchuk zone* (Kyiv: Nika-Center)

[8] Shybetskyi I O, Shestopalov V M, Pochtarenko V I, Borysova T A and Shurpach N O 2022 *Geological Journal* 3–23 URL https://doi.org/10.30836/igs.1025-6814.2022.1.247970

[9] Panova O A, Pryvalov V A, Izart A, Alsaab D and Antsiferov A V 2009 Geodynamical Events (Coal-and-Gas Outbursts) in the Donets Basin, Ukraine *71st EAGE Conference and Exhibition incorporating SPE EUROPEC 2009* (European Association of Geoscientists & Engineers) ISSN 2214-4609 URL https://doi.org/10.3997/2214-4609.201400154

[10] Goshovskyi S and Zurian O 2021 Implementation of aerospace monitoring to identify ecologically hazardous areas of methane leak from the sea bed *15th International Conference Monitoring of Geological Processes and Ecological Condition of the Environment* vol 1 (European Association of Geoscientists & Engineers) pp 1–5 ISSN 2214-4609 URL https://doi.org/10.3997/2214-4609.20215k2051

[11] Trofymchuk O, Anpilova Y, Yakovlev Y, Kreta D and Shekhunova S 2020 Assessment of solotvyno agglomeration mines flooding impact on water resources with gis *Water Supply and Wastewater Disposal: Designing, Construction, Operation and Monitoring* ed Henryk Sobczuk B K (Politechnika Lybelska) pp 315–327

[12] Trofymchuk O, Yakovliev Y, Anpilova Y, Myrontsov M and Okhariev V 2021 Ecological Situation of Post-mining Regions in Ukraine *Systems, Decision and Control in Energy II* ed Zaporozhets A and Artemchuk V (Cham: Springer International Publishing) pp 293–306 ISBN 978-3-030-69189-9 URL https://doi.org/10.1007/978-3-030-69189-9_17

[13] Anpilova Y, Yakovliev Y, Trofymchuk O, Myrontsov M and Karpenko O 2022 Environmental Hazards of the Donbas Hydrosphere at the Final Stage of the Coal Mines Flooding *Systems, Decision and Control in Energy III* ed Zaporozhets A (Cham: Springer International Publishing) pp 305–316 ISBN 978-3-030-87675-3 URL https://doi.org/10.1007/978-3-030-87675-3_19

[14] Dolin V, Yakovlev Y, Shcherbak O and Kutska Y 2015 Evolution of profile of radiohydrogeochemical anomaly of tritium contamination within affected zone of surface radioactive waste repository *14th EAGE International Conference on Geoinformatics - Theoretical and Applied Aspects, Geoinformatics 2015* (European Association of Geoscientists & Engineers) pp 1–6 ISSN 2214-4609 URL https://doi.org/10.3997/2214-4609.201412368

[15] Lyuta N and Sanina I 2021 Assessing changes in groundwater quality of uppermost aquifers over time *15th International Conference Monitoring of Geological Processes and Ecological Condition of the Environment* (European Association of Geoscientists & Engineers) pp 1–5 ISSN 2214-4609 URL https://doi.org/10.3997/2214-4609.20215k2039

[16] Younger P L, Coulton R H and Froggatt E C 2005 *Science of The Total Environment* **338**(1) 137–154 ISSN 0048-9697 Bioremediation of Acid Mine Drainage: The Wheal Jane Mine Wetlands Project URL https://doi.org/10.1016/j.scitotenv.2004.09.014

[17] Ulytsky O A and Boyko K S 2021 *Ukrainian Journal of Remote Sensing* **8**(1) 18–25 URL https://doi.org/10.36023/ujrs.2021.8.1.188

[18] Gordyenko V V, Gordienko I V, Zavgorodnyaya O V, Logvinov I M and Tarasov V N 2015 *Donbas (geophysics, underground processes)* (Kyiv: Logos)

[19] Klyushnikov M N, Kudelya A D, Onishchenko A M and Nerodenko V M 1958 *Geological map of the USSR on a scale of 1: 200,000. Sheet M-37-XXXII*

[20] Tarasevich G L 1959 *Geological map of the USSR on a scale of 1: 200,000. Sheet M-37-XXXIII*

[21] Maidanovych I A and Radzyvyll A Y 1984 *Peculiarities of tectonics of coal basins of Ukraine* (Kyiv: Naukova dumka)

[22] Gintov O B, Orlyuk M I, Entin V A, Pashkevich I K, Mychak S V, Bakarzhieva M I, Shimkiv L M and Marchenko A V 2018 Megablock structure of the Ukrainian shield according to modern geophysical and geological data *Proceedings of the Scientific conference dedicated to the 100-year anniversaries of the National Academy of Sciences and the Geological Service of Ukraine "Geology and minerals of Ukraine"* (Kyiv) pp 46–48

[23] Yevgrashkina G, Kharytonov M, Klimkina I and Shikula E 2021 *E3S Web of Conferences* **280** 06007 URL https://doi.org/10.1051/e3sconf/202128006007

[24] Dudnyk V A and Korchemagin V A 2004 *Scientific papers of DONNTU. Series: The mining and geology* **81** 83–91

[25] Lyalko V I, Romanciuc I F, Yelistratova L A, Apostolov A A and Chekhniy V M 2020 *Journal of Geology, Geography and Geoecology* **29**(1) 102–110 URL https://doi.org/10.15421/112010

[26] Apostolov O A, Elistratova L O, Romanchuk I F and Chekhniy V M 2020 *Ukrainian Geographical Journal* (1) 16–25 URL https://doi.org/10.15407/ugz2020.01.016

[27] Galvão L S, Formaggio A R and Tisot D A 2005 *Remote Sensing of Environment* **94**(4) 523–534 URL https://doi.org/10.1016/j.rse.2004.11.012

[28] Sriwongsitanon N, Gao H, Savenije H H G, Maekan E, Saengsawang S and Thianpopirug S 2015 *Hydrology and Earth System Sciences* **12** 8419–8457 URL https://doi.org/10.5194/hessd-12-8419-2015

[29] Brown L 2000 *Remote Sensing of Environment* **71**(1) 16–25 URL https://doi.org/10.1016/

s0034-4257(99)00035-8

[30] Abdullah H, Skidmore A K, Darvishzaden R and Heurich M 2018 *Remote Sensing in Ecology and Conservation* **5**(1) 87–106 URL https://doi.org/10.1002/rse2.93

[31] Pinder III J E and McLeod K W 1999 *Photogrammetric Engineering and Remote Sensing* **65**(4) 495–501 URL https://www.asprs.org/wp-content/uploads/pers/1999journal/apr/1999_apr_495-501.pdf

[32] Sakhatsky A I 2009 *Methodology of application of multispectral satellite data under the solution of hydrological problems* Thesis for the degree of Doctor of Science in geology, specialty 05.07.12 Remote Aerospace Research State Institution "Scientific Centre for Aerospace Research of the Earth IGS NAS of Ukraine" Kyiv

[33] Yehorshyn O O, Malyarets L M and Sinkevich B V 2009 *Handbook of mathematical statistics with examples of calculations in MatLab: educational and practical guide* vol 2 (Kharkiv: Khneu)

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Impact of pesticides on the respiration of *Planorbarius* (superspecies) *corneus* s. l. allospecies (Mollusca, Gastropoda, Pulmonata, Planorbidae) from the Ukrainian river network

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Impact of pesticides on the respiration of *Planorbarius* (superspecies) *corneus* s. l. allospecies (Mollusca, Gastropoda, Pulmonata, Planorbidae) from the Ukrainian river network

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Abstract. We studied the impact of different concentrations in water environment of the pesticides widely used in Ukraine (insecticide "Actor", fungicide "Scooter", and herbicide "Titus-C") on the features of pulmonary and surface respiration of *Planorbarius* (superspecies) *corneus* s. l. vicaristic genetic allospecies ("western" and "eastern"). Pesticides get into the mollusc organisms percutaneously through the covers of their body during their respiration and, in much less amounts, with the food. Both the allospecies are characterized by bimodal respiration mode. It was established that the used pesticides in the concentration range 10-50 mg/L caused the rapid development of pathological process (intoxication). The lethality of experimental animals occurred due to the asphyxia and heart paralysis, caused by the intensive mucus production and destruction of the respiratory epithelium: first in body covers, later – in lungs. "Eastern" allospecies appeared to be more sensitive and less durable for all used pesticides, so it tends more to regress under the high contamination of water environment by these toxicants.

1. Introduction

Pesticides now belong to the most widespread among artificially synthesized stable organic toxicants in Ukrainian river network. Many years of sometimes uncontrolled their use in agriculture in the last decade caused the contamination of surface waters and deterioration of their nature ecological balance [1]. They get into the water ecosystems due to the flow of melted, rain and ground waters from the treated soils and due to blowing by wind during cultivation of lands near water bodies. Because of the cumulative features, these toxicants are accumulated and circulate in the tissues and organs of almost all the hydrobionts, and involve into the trophic chains of water bodies, increasing their concentration in times [2].

The toxical impact of pesticides on the water animals largely depends on their ability to be consumed (bio-availability), to accumulate in organisms (bio-concentration) and in trophic chains (bio-magnification), their dose power and stability in the environment [3]. The harmful action of these toxicants on the hydrosphere consists of the change of physico-chemical properties of water environment – changing its oxygen mode, decrease of phyto-/zooplankton amount, direct harmful action on ichthyofauna, gradual loss of turgor and death of higher aquatic plants [4–7].

Pesticides used for intensification of agriculture production are divided in three main groups: herbicides to fight the higher plants, insecticides for insect defense, fungicide against the fungal pathogens. Insecticide are the most acute toxic among all and lead to the decrease of water animal growth causing various metabolic and reproductive deteriorations [8, 9]. Fungicides are accumulated in water environment and in hydrobionts' food chain objects causing their intoxication and death. Herbicides worsen the water quality (bad taste and smell) decreasing the oxygen level, food supply and bioproductivity of hydrobionts [10].

Under improper use of pesticides, the danger arises for existence of the main water ecosystems, ecological links between water organisms are disturbed, their biodiversity is lost. To reveal the consequences of these toxins' impact on the water bodies and their inhabitants, more and more often the experimental method of bio-testing is used in water toxicology. This procedure consists of identification of toxicity of chemical compounds for hydrobionts by the quantitative changes of their vital functions. As test-objects one could use the animals highly-sensitive to the action of these compounds and able to accumulate them in organisms. The vicaristic genetic allospecies of *Planorbarius* (superspecies) *corneus* sensu lato, widespread in Ukrainian river network, belong to such animals. Until now, there were no data on functioning of their respiration system under the impact of the most widespread pesticides.

The aim of present study was to identify the features of impact of three different widespread in Ukraine pesticide groups (insecticides, fungicide, herbicide) in different concentrations on the indexes of pulmonary and surface (diffusive) respirations in "western" and "eastern" *P. corneus* s. l. allospecies, and to estimate the availability of these molluscs to be used as bio-indicators for monitoring the state of surface waters under their pollution of used toxicants.

2. Material and methods

2.1. Collection of molluscs

We collected a total of 1358 individuals of P. *corneus* s. l. in July-August of 2021. Among them, 679 individuals were from the "western" allospecies, collected at the Hnyla river (Horodnytsia village, Ternopil region, $49°24'38.5''N$ $26°01'05.2''E$), and 679 individuals were from the "eastern" allospecies, collected at Psel river (Sumy, Sumy region, $50°54'26.5''N$ $34°48'18.1''E$). The allospecies were identified based on their conchiological traits.

2.2. Acclimatization and care of molluscs

Upon collection, the molluscs were transported to the laboratory and subjected to a 15-day acclimatization period. During this time, they were housed in 10 L tanks at a density of 4 individuals per liter of water. The water temperature was maintained at $20 - 22°C$, with a pH range of 7.5-8.6 and oxygen levels of 7.5-8.6 mg/L. The molluscs were provided with daily environmental changes and were fed a diet consisting of *Cladophora sp., Miriophyllum spicatum* L., and *Alisma plantago-aquatica* L. mixture collected from the collection sites.

2.3. Experimental procedures and toxicants

We conducted both pilot and main experiments following standard methods. As toxicants, we used the insecticide "Actor" and fungicide "Scooted" (from "Simeinyi Sad" Ltd, Ukraine), as well as the herbicide "Titus-C" (from "Dunlop" Ltd, Ukraine) at concentrations of 10, 20, 30, 40, and 50 mg/L. These solutions were prepared using two-days aged tap water from the Zhytomyr water supply. The exposure period was 7 days.

2.4. Monitoring behavioral and physiological reactions

To assess the effects of the pollutants, we monitored the behavioral and physiological reactions of the molluscs [11]. The number of "inspirations" was determined by counting the emergences of each individual from the water surface tension film to which they were attached using their pneumostome, a process accompanied by a clear clapping sound. This behavior signified the initiation of "inspiration", where atmospheric air was drawn through the pneumostome into the respiration syphon and then into the mollusc's pulmonary cavity.

2.5. Surface respiration assessment

Surface respiration intensity was estimated by measuring the survival duration of experimental molluscs that were deprived of pulmonary respiration. These molluscs were placed at the bottom of an aquarium in small, water-permeable boxes made from densely and finely perforated plastic sheathing, with weights attached to the bottom. We analyzed the obtained results using basic variation statistical methods.

Table 1. The impact of pesticides in different concentrations (mg/L) on indexes of lung respiration of P. *corneus* s. l. allospecies. "Western" allospecies.

Pesticide	Concentraion, mg/L	n	Daily number of inspirations $M \pm m$	Interval between inspirations, min $M \pm m$	Duration of inspiration, min $M \pm m$	Volume of inspiration, number of bubbles $M \pm m$
Insecticide "Actor"	Control	20	15.78±1.32	64.42±1.16	20.59±1.44	18.46±1.18
	10	18	16.15±1.17	62.41±1.32	21.14±1.06	19.21±1.25
	20	19	17.37±1.11	55.12±1.28*	23.41±1.15*	21.39±1.23*
	30	19	19.42±1.29*	43.24±1.06**	26.76±1.23**	27.18±1.27**
	40	20	12.23±1.07*	93.62±1.18**	15.79±1.16**	11.25±1.33**
	50	20	10.82±1.35*	110.58±1.03**	12.64±1.03**	10.31±1.42**
Fungicide "Scooter"	Control	20	16.06±1.12	63.54±1.14	21.26±1.18	19.33±1.24
	10	19	16.73±1.21	59.12±1.35	22.34±1.19	20.12±1.14
	20	19	17.86±1.19	52.37±1.11*	24.12±1.13*	22.22±1.31*
	30	20	19.87±1.26*	41.52±1.15**	27.32±1.17**	28.26±1.05**
	40	20	12.57±1.14*	91.71±1.27**	16.12±1.20**	11.76±1.23**
	50	19	11.38±1.34*	108.24±1.18**	12.91±1.22**	10.87±1.14**
Herbicide "Titus-c"	Control	20	16.13±1.29	62.40±1.16	21.67±1.26	19.86±1.20
	10	19	16.89±1.42	57.67±1.39	22.63±1.24	20.27±1.16
	20	19	18.06±1.37	50.46±1.21*	24.66±1.12*	22.16±1.25*
	30	20	20.22±1.02*	40.25±1.36**	28.05±1.28**	29.10±1.09**
	40	18	13.07±1.24*	88.62±1.18**	16.58±1.10**	12.46±1.13**
	50	19	12.16±1.03*	100.36±1.14**	13.46±1.19**	11.63±1.34**

Note: n – number of individuals studied; MPC – maximum permissible concentration of ions in the water; $M \pm SE$ – mean value of index and its standard error; * – statistically significant differences ($p \leq 0.05$); ** – highly significant differences ($p \leq 0.001$).

2.6. Ethical compliance

Throughout the experiments, we strictly adhered to ethical norms and principles governing research involving living organisms, in full compliance with the current laws of Ukraine. As part of our ethical commitment, we emphasize the following:

1 *Invertebrate research*: the experimental molluscs in our study belong to the category of invertebrates, and we ensured that ethical considerations for their welfare were upheld.

2 *Compliance with Ukrainian laws*: we affirm that our research is fully compliant with the prevailing laws and regulations of Ukraine, including those governing the ethical treatment of research subjects.

3 *Ethical review*: this research received approval from the Human or Animal Ethics Committee at Zhytomyr Ivan Franko State University. The committee reviewed and approved the ethical aspects of our study to ensure the humane treatment of the experimental subjects.

Table 2. The impact of pesticides in different concentrations (mg/L) on indexes of lung respiration of P. *corneus* s. l. allospecies. "Eastern" allospecies.

Pesticide	Concentraion, mg/L	n	Daily number of inspirations $M \pm m$	Interval between inspirations, min $M \pm m$	Duration of inspiration, min $M \pm m$	Volume of inspiration, number of bubbles $M \pm m$
Insecticide "Actor"	Control	20	14.23±1.28	78.64±1.12	18.56±1.13	17.34±1.25
	10	19	14.61±1.19	75.36±1.21	19.37±1.36	18.04±1.33
	20	20	15.34±1.08	68.13±1.25*	21.46±1.18*	20.08±1.15*
	30	19	17.49±1.35*	54.61±1.11**	24.38±1.11**	25.12±1.29**
	40	19	11.15±1.25*	112.46±1.06**	13.18±1.21**	10.52±1.17**
	50	20	9.85±1.23**	130.02±1.13**	11.12±1.36**	9.03±1.06**
Fungicide "Scooter"	Control	20	14.41±1.32	76.82±1.27	19.06±1.38	17.53±1.12
	10	20	15.16±1.25	71.12±1.35	20.48±1.39	18.78±1.31
	20	19	16.32±1.23	63.16±1.02*	22.14±1.20*	20.41±1.32*
	30	19	18.11±1.42*	51.21±1.11**	25.16±1.19**	26.82±1.23**
	40	20	11.57±1.10*	106.27±1.19**	13.52±1.27**	11.06±1.33**
	50	19	10.12±1.19*	126.08±1.22**	11.63±1.45**	9.89±1.25**
Herbicide "Titus-c"	Control	20	14.78±1.21	74.41±1.13	19.72±1.24	18.12±1.22
	10	19	15.48±1.32	69.25±1.17	20.64±1.12	19.21±1.16
	20	19	16.62±1.20	60.12±1.01*	22.82±1.06*	21.42±1.13*
	30	19	18.55±1.13*	47.82±1.15**	26.79±1.36**	27.14±1.31**
	40	20	11,62±1,27*	104,29±1,33**	13,74±1,12**	11,16±1,41**
	50	20	10,59±1,38*	120,10±1,08**	12,08±1,17**	10,11±1,28**

Note: n – number of individuals studied; MPC – maximum permissible concentration of ions in the water; $M \pm SE$ – mean value of index and its standard error; * – statistically significant differences ($p \leq 0.05$); ** – highly significant differences ($p \leq 0.001$).

3. Results and discussion

Pesticides can get into the molluscs' organisms percutaneously through their body covers of during respiration and in much less amounts from their food. Allospecies of P. *corneus* s. l. possess the bimodal respiration mode. The lungs are the adaptive acquisition in these molluscs for the new environment, where they found themselves in ancient times due to their forced transition from water to land environment, acquiring the ability to breathe by atmospheric air. The pulmonary respiration is performed by them via the periodical emergences under the water surface tension film to take the air through pneumostome. The surface respiration is established due to the diffusive income of water-solved oxygen in the molluscs' blood through their epithelial body covers and adaptive gill of quite large area. It is known, that efficiency of oxygen supply is almost equal for both modes: 0.025 and 0.03 O_2 (mg)/L (per 1 g of fresh mass, respectively).

We established that pesticides in the concentration range from 10 to 50 mg/L caused the rapid development of pathological process in ramshorn allospecies. Under the 10 mg/L concentration, obtained indexes of both pulmonary and surface respirations were close to those found in control group (tables 1-4), which corresponds with a latent phase of intoxication.

Under the concentrations of mentioned pesticides of 20-30 mg/L, the indexes of both respiration modes demonstrated the development of adaptive process in form of stimulation of all studied indexes in studied allospecies, which increased with increasing of used toxicant's concentration. This corresponds with the next phase of pathological process – stimulation. Studied molluscs showed the increase of daily number of "inspirations" and of their duration

Table 3. The impact of pesticides in different concentrations (mg/L) on indexes of direct diffusive respiration of *P. corneus* s. l. allospecies. "Western" allospecies.

Pesticide	Concentration, mg/L	n	$M \pm m$
Insecticide "Actor"	Control	18	47.36±2.65
	10	17	48.45±3.41
	20	19	50.62±2.48
	30	20	55.02±2.67*
	40	18	22.53±3.12**
	50	17	20.14±2.79**
Fungicide "Scooter"	Control	20	47.89±3.36
	10	19	49.06±3.28
	20	17	51.24±3.13
	30	18	56.12±2.78*
	40	19	23.20±3.46**
	50	17	20.72±3.61**
Herbicide "Titus-c"	Control	18	48.06±2.03
	10	19	49.57±2.39
	20	18	52.15±3.08
	30	20	57.34±2.82*
	40	18	23.65±2.81**
	50	19	21.23±3.08**

Note: n – number of individuals studied; MPC – maximum permissible concentration of ions in the water; $M \pm SE$ – mean value of index and its standard error; * – statistically significant differences ($p \leq 0.05$); ** – highly significant differences ($p \leq 0.001$).

Table 4. The impact of pesticides in different concentrations (mg/L) on indexes of direct diffusive respiration of *P. corneus* s. l. allospecies. "Eastern" allospecies.

Pesticide	Concentration, mg/L	n	$M \pm m$
Insecticide "Actor"	Control	19	41.12±2.35
	10	18	42.36±3.78
	20	18	44.12±3.16
	30	19	48.56±3.67*
	40	17	19.23±2.05**
	50	18	18.21±2.28**
Fungicide "Scooter"	Control	19	41.36±3.45
	10	18	42.82±3.13
	20	17	45.06±2.75
	30	18	48.86±3.12*
	40	19	20.13±2.16**
	50	18	18.72±2.25**
Herbicide "Titus-c"	Control	18	41.58±2.19
	10	19	43.04±2.71
	20	18	45.69±3.28
	30	19	49.03±3.63*
	40	17	20.48±2.49**
	50	19	19.02±3.10**

Note: n – number of individuals studied; MPC – maximum permissible concentration of ions in the water; $M \pm SE$ – mean value of index and its standard error; * – statistically significant differences ($p \leq 0.05$); ** – highly significant differences ($p \leq 0.001$).

by 1.1 times, intervals between them by 1.1-1.3 times, and "inspiration" volume by 1.3 times ($p \leq 0.05$–0.001). We registered also the increase of the surface respiration indexes (estimated by the survival rate without pulmonary respiration) by 1.1 times ($p \leq 0.05$).

However, under the impact of higher toxicants' concentrations (40 and 50 mg/L), the level of mentioned way of defense appeared to be insufficient to successfully defeat the harmful action of toxic agent. Due to that, the experimental molluscs rapidly developed the depressive phase of intoxication process, which was caused by structural and functional damages of both their lung and cover epitheliums; it was quickly replaced by sub-lethal and lethal phases. Comparing to the control group, experimental P. *corneus* allospecies demonstrated the decrease of daily "inspiration" number by 1.2-1.3 times, interval between them by 1.6 times, "inspiration" duration by 1.3-1.4 times, and "inspiration" volume by 1.6 times ($p \leq 0.05$–0.001). Noteworthy, the survival of the studied allospecies without ability to perform the pulmonary respiration decreased by 2.1 times ($p \leq 0.001$).

Changes in both respiration modes in studied molluscs were followed with manifestations of fast ethological and physiological responses-reactions to the toxic environment impact. Avoiding of toxic environment is one of the first fast behavioral defensive reactions, which such molluscs possess. It is caused by the presence in P. *corneus* s. l. allospecies the neural connection between their organs receipting the chemical stimuli (osphradia) and the muscles responsible for movement in space as a result of stimulus obtained. This reaction, however, was observed during long time only under the low (10 and 20 mg/L) and moderate (30 mg/L) concentrations of used pesticides, and quite quickly fully slowed down under the high (40 and 50 mg/L) concentrations.

The lethality of experimental molluscs occurred due to the asphyxia and heart paralysis, caused by the intensive mucus production and destruction of the respiratory epithelium: first in body covers, later – in lungs. In both studied allospecies the fast and powerful watering of epithelium cells caused first the rapid growth of cell elements volume due to edema, which, although, strongly crimpled and destroy soon, and finally were exfoliated. The abruption of their leftovers was sometimes followed with disruption of underlying tissues and bleeding, less often with powerful bleeding. Similar deteriorations usually occurred earlier and manifested brighter in “eastern” allospecies individuals. That may be considered as the consequence of this allospecies range being spread on the territories with higher climate drought comparing to those inhabited by “western” allospecies.

4. Conclusions

The indexes of pulmonary and surface diffusive respirations in P. *corneus* s. l. allospecies showed their clear dependence on the environmental pesticide concentration. Toxic-resistance of “eastern” allospecies to the used toxicants appeared lower than in “western” allospecies. That’s why the first appeared more sensitive and less endurance to the impact of used toxic agent.

Allospecies of ramshorn can be recommended for use in the system of ecological monitoring as indicator species. As the aim functions, the indexes of pulmonary and surface respirations should be considered.

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References

[1] Kolesnyk N 2015 *Fisheries science of Ukraine* **4**(34) 31–53 URL https://doi.org/10.15407/fsu2015.04.031
[2] Shefali, Kumar R, Sankhla M S, Kumar R and Sonone S S 2021 *Biointerface Research in Applied Chemistry* **11**(3) 10131–10140 URL https://doi.org/10.33263/BRIAC113.1013110140
[3] Maurya P K, Malik D S and Sharma A 2019 Impacts of pesticide application on aquatic environments and fish diversity *Contaminants in Agriculture and Environment: Health Risks and Remediation* (India: Agro Environ Media) chap 9, pp 111–128 URL https://doi.org/10.26832/AESA-2019-CAE-0162-09
[4] Sytnyk Y, Kolesnik N and Bersan T 2012 *Fisheries science of Ukraine* **3**(21) 8–13 URL https://fsu.ua/index.php/en/2012/3-2012-21/2012-03-008-013
[5] DeLorenzo M E, Scott G I and Ross P E 2001 *Environmental Toxicology and Chemistry* **20**(1) 84–98 URL https://doi.org/10.1002/etc.5620200108
[6] Severo E S, Marins A T, Cerezer C, Costa D, Nunes M, Prestes O D, Zanella R and Loro V L 2020 *Ecotoxicology and Environmental Safety* **190** 110071 ISSN 0147-6513 URL https://doi.org/10.1016/j.ecoenv.2019.110071
[7] Rani R, Sharma P, Kumar R and Hajam Y A 2022 Effects of heavy metals and pesticides on fish *Bacterial Fish Diseases* ed Dar G H, Bhat R A, Qadri H, Al-Ghamdy K M and Hakeem K R (Academic Press) chap 3, pp 59–86 URL https://doi.org/10.1016/B978-0-323-85624-9.00016-6
[8] Stara A, Pagano M, Capillo G, Fabrello J, Sandova M, Vazzana I, Zuskova E, Velisek J, Matozzo V and Faggio C 2020 *Science of the Total Environment* **700** 134914 URL https://doi.org/10.1016/j.scitotenv.2019.134914
[9] Ayad M A, Fdil M A and Mouabad A 2011 *Archives of Environmental Contamination and Toxicology* **60** 462–470 URL https://doi.org/10.1007/s00244-010-9549-7
[10] Helfrich L A, Weigmann D L, Hipkins P A and Stinson E R 2009 Pesticides and aquatic animals: A guide to reducing impacts on aquatic systems URL https://vtechworks.lib.vt.edu/bitstream/handle/10919/48060/420-013_pdf.pdf
[11] Babych Y V, Kyrychuk G, Romaniuk R, Stadnychenko A and Uvayeva O 2023 *Folia Malacologica* **31** 9–18 ISSN 1506-7629 URL https://doi.org/10.12657/folmal.031.002

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Environmental safety of soil genetic horizons in the impact zone of Lviv city landfill (Ukraine)

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Abstract. Landfills cause significant technogenic pressure on the environment, being the center of depositing large volumes of hazardous materials in a relatively small area. Interacting with each other they form hazardous substances and compounds. In this study, we describe three genetic soil horizons that are within the impact zone of the landfill of a city of millions of people. It was established that the distribution of mobile forms of heavy metals according to the profile of the studied soils tended to gradual decrease with depth. When describing the genetic horizons of three profiles located in the impact zone of the landfill, it was established that the content of heavy metals in them does not exceed the MPC, except for Pb. The soil at the foot of the landfill turned out to be the most contaminated with heavy metals (profile No. 3). The activity of micromycetes in this soil was the lowest here. In general, all soils in the impact area of the landfill are impoverished in micromycete distribution. The taxonomic composition of mycelial fungi and the identified species' ecological and biological characteristics indicate significant ecosystem pollution by household waste.

1. Introduction

The edaphotope has a significant influence on the development of phytocenoses. Depending on its physicochemical, mechanical, and acidic properties, vegetation in landfills develops in different ways. In the impact zone of technogenic landscapes, there is an increased radiation background and increased activity of radionuclides in edaphotops. Numerous studies of edaphotopes of technogenic landscapes are being conducted in Ukraine. According to Uzbek and Halahan, in the technogenic landscapes, the edaphotope is a man-made, spatially limited bioinert system that is in constant development under the influence of soil formation factors [1]. In work [2], the contribution of the moss cover *Campylopus introflexus* (Hedw.) Brid. in the restoration of technogenic substrates due to the improvement of their edaphotopic properties is defined.

A carbon source of 4–6 g/L at pH 5–8 was found to enhance the heavy metal bioremediation potential of *Pseudomonas aeruginosa, Enterobacter cloacae, and Klebsiella edwardsii* isolated in a landfill in Lagos, Nigeria. The role of native bacteria in the remediation process can be optimized and used to standardize on-site bioremediation as well as establish biodegradation protocols. Great benefits can be provided by effective remediation of contaminated soils by improving soil condition and yield [3].

Soil microscopic fungi are very sensitive to changes in soil characteristics, so they can serve as indicators of its condition [4]. Micromycetes are not only an integral component of terrestrial and aquatic biocenoses, which control a wide range of biosphere functions, but also the main group of microorganisms responsible for both the synthesis and destruction of humic substances in the soil. Technogenic impact on the environment, as well as the rapid development of nanotechnology, make the problem of studying the interaction of micromycetes with organic matter of natural origin urgent.

The main feature of micromycetes is that they dominate soil microbiota. They represent the most specific group of microorganisms that participate in the mineralization of organic plant and animal residues and the formation of humus. The rate of decomposition of organic substances is determined by such factors as the chemical composition of the substrate, the efficiency of providing nitrogen to microorganisms, the composition of the microbial environment, and environmental conditions. Fungi under aerobic conditions are capable of decomposing even complex polymer compounds, for example, lignin, unlike other microorganisms, which are more conducive to the mineralization of low molecular weight organic compounds. Some soil fungi are able to decompose humus and use it as the only source of nitrogen and (or) carbon. At the same time, micromycetes participate not only in the process of destruction but also in formation of humic substances [5].

It has been established that the contribution of fungal bioaugmentation to the decontamination of soil has been clearly observed, and therefore mixed fungal organisms may serve as future bioremediation agents for contaminated areas [6]. It has also been proven that the synthesized rhamnolipids can significantly increase the activity of soil enzymes to facilitate the digestion and transformation of heavy metals from the soil to the aerial part of ryegrass [7].

The study of the enzymatic activity of the soils of technogenic territories of the Nemyriv sulfur deposit is shown in the paper [8]. It was established that the low activity of oxidoreductases and urease in the soils of the former development of sulfur deposits is a consequence of significant inhibition of the activity of soil microflora – the main producer of enzymes – by technogenic factors. The formation of a phytoremedial cover on the surface of devastated landscapes of coal mining is given in the article [9]. The role of plant cover in the restoration of disturbed lands has been established.

It should be noted that the conditions of local growth on the landfills' surfaces negatively affect the growth and development of vegetation. Among the analyzed metals, iron reached the highest values in samples of *Tanacetum vulgare L.*, namely, stems (103.4–6564.6 mg/kg of dry matter), roots (6563.6–33,036.6 mg/kg of dry matter), leaves (535.1–11.275 mg/kg of dry matter), and soil (12.389–39.381.9 mg/kg of dry matter). Cd, as well as Cr, Ni, and Zn, accumulate mainly in the leaves, while Co, Cu, Fe, Hg, Mn, and Pb accumulate mainly in the roots of *T. vulgare* [10]. However, grass species that are tolerant to the high content of heavy metals in red mud dumps were investigated [11]. Namely, based on the metal resistance index, 51.4, 10.8 and 37.8% of grass species showed sensitive, moderate, and high metal resistance – *Brachiaria mutica, Cynodon dactylon, Dactyloctenium aegyptium, Digitaria ischaemum, Digitaria longiflora, Eragrostis cynosuroides, Launaea asplenifolia, Parthenium hysterophorus, Sporobolus diander, Stylosanthes scabra.* The research suggests a potential pathway for phytomanagement of abandoned red mud landfills through remediation using dominant metal-tolerant plant species [11].

The fact that landfills are polluting objects has been described by many scientists in their works. The impact of landfills on the human body is constantly being studied. Scientists have found that solid waste from a modern city contains more than 100 items of extremely toxic substances, including dyes, pesticides, solvents, medicines, used motor oils, phytochemicals, etc. Thermometers, fluorescent lamps, and various appliances contain mercury, an extremely dangerous substance because it is a volatile metal that can evaporate at low temperatures and, when exposed to microorganisms in landfills, turns into methylmercury, which can cause massive poisoning if ingested through water and food.

One of the world's largest landfills is the Lviv Municipal Solid Waste Landfill, which was included in the list of the 100 Greatest Environmental Disasters of Ukraine. Due to violations of the landfill's operating requirements, it has turned into a spontaneous landfill. The landfill is 3 km from the northern border of Lviv, near the village of Velyki Hrybovychi. It has been operating since 1957. Over the years, it has accumulated over 50 million cubic meters of waste. Until 1990, not only municipal solid waste, but also toxic industrial waste was stored within its boundaries. According to rough estimates, the amount of waste reached 2 million tons. In addition to garbage, more than 200 thousand tons of acidic tar, waste from the Lviv Oil Refinery, which is no longer in operation, has accumulated at the landfill. The thickness of the garbage layer in the southeastern part of the landfill reaches 50 meters, while in the northwestern part, it varies from 1-3 to 10 meters. Its total area is 33.6 hectares.

Thus, the investigation of edaphotopes of technogenic landscapes, including landfills, is relevant from the point of view of reducing their harmful effects and returning land to national economic use.

2. Materials and methods

Physico-chemical investigation of edaphotopes of soil horizons within the impact zone of the Lviv city landfill were carried out according to the state standards of Ukraine [12–14].

The surveys were conducted in July 2020, before the start of the reclamation of the Lviv landfill.

The content of mobile forms of heavy metals in edaphotops was determined: mobile forms of copper, zinc, cobalt were determined by the Rinkis method, lead, cadmium – by the atomic absorption method. They were also guided by the state standards [15].

Determination of the quantitative and qualitative composition of micromycetes of technogenic edaphotopes of landfills was carried out by sowing soil suspension from decimal dilutions on wort-agar and Chapek's agar medium. Cultivation of the studied samples was carried out at +26. . . +28 °C. Isolated cultures were studied with a microscope "MBI-6" according to the method adopted in mycological studies [16]. The study of isolated micromycetes was carried out according to the generally accepted definition [5].

3. Results and discussion

For investigation of the influence of landfills' hazardous factors on the formation of the soil profile, the soil profile cuts were made, from which mixed soil samples were selected according to genetic horizons. Mycological and agrochemical analyzes were carried out, as well as analyzes for the content of nutritious minerals, heavy metals, and toxic elements (figure 1).

It should be noted that in the impact zone of the Lviv city landfill, we have carried out ecological monitoring of the hazardous substances distribution in edaphotopes as a result of the spillage of acid tar storage facilities, two lakes of which are stored on the southern side of the top. It has been established that hazardous substances expand to a distance of 1,500 m from the foot of the landfill.

3.1. Genetic soil horizon No. 1

The peatland (profile No. 1) is located within a radius of 2 km east of the foot of the landfill. The land belongs to the Dublyany City Council of the Lviv District (Lviv Region). In terms of peat reserves, this deposit was one of the largest in the world. After the Second World War, the local population made peat briquettes by hand to heat houses. As a result, the peatland lost a significant part of its capacity. At the moment, agricultural products are grown on peatlands, which is prohibited due to the deposition of polluting substances in peat, including leachates from landfills. The danger of landfill leachates is described in scientific works [17–19]. Malovanyy et al [20] presents a rational scheme of the biological conveyor of an open-type installation for cleaning landfill leachate. Laboratory studies were conducted to determine the efficiency of using nozzles for the immobilization of microbiocenosis in aerated lagoons, which are used to clean landfill leachate. The interest in studying the physical and chemical properties of peat, which is

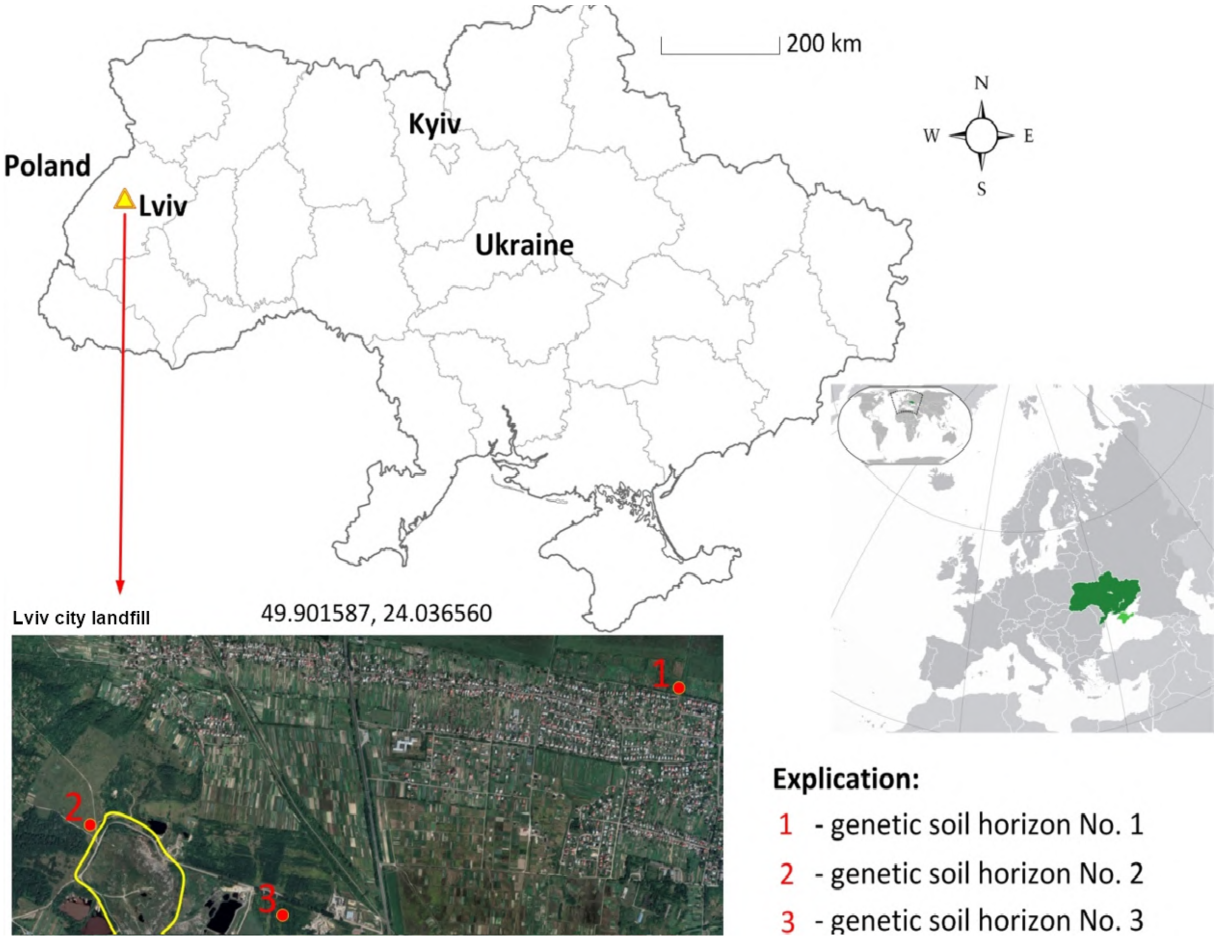

Figure 1. Location of objects of research in the impact zone of the Lviv municipal landfill.

located in the zone of influence of landfills, is caused by the fact that it is the main component of the landscape, in which various biogeochemical and migration processes occur, being a natural sorbent of various chemicals and an indicator of the degree of the natural ecosystem destruction.

When describing the deep peatland, it was found that the content of heavy metals in the surface layer T1 significantly exceeds the indicators in the genetic horizon T2 (figure 2, figure 3).

In view of the above-mentioned data, it can be stated that the content of cobalt in peatlands does not exceed the MPC, which is 5 mg/kg. The mercury content is 250 times lower than the MPC, which is 2 mg/kg. The cadmium content is twice as low as the permissible standard of 0.7 mg/kg. In general, the presence of this toxicant in the soil section with a concentration of 0.5 MPC is a negative phenomenon. The source of cadmium in landfills is waste containing varnishes and paints, fluorescent lamps, batteries, etc. Cadmium sulfide is the basis of yellow paints used in vehicle painting, textile production, and soap making. Cadmium selenide is used as a red dye. Cadmium is also used in semiconductor materials, cryogenic technology, lead-cadmium and mercury-cadmium elements of reserve batteries, and anti-corrosion metal coatings.

The distribution of the content of mobile forms of heavy metals according to the profile of the studied soils is demonstrated by their gradual decrease with depth.

The physical and chemical composition analysis of section No. 1 showed that the peatland has a significant supply of nitrogen (56.05 mg/100 g) and potassium (58.5 mg/100 g) nutrients

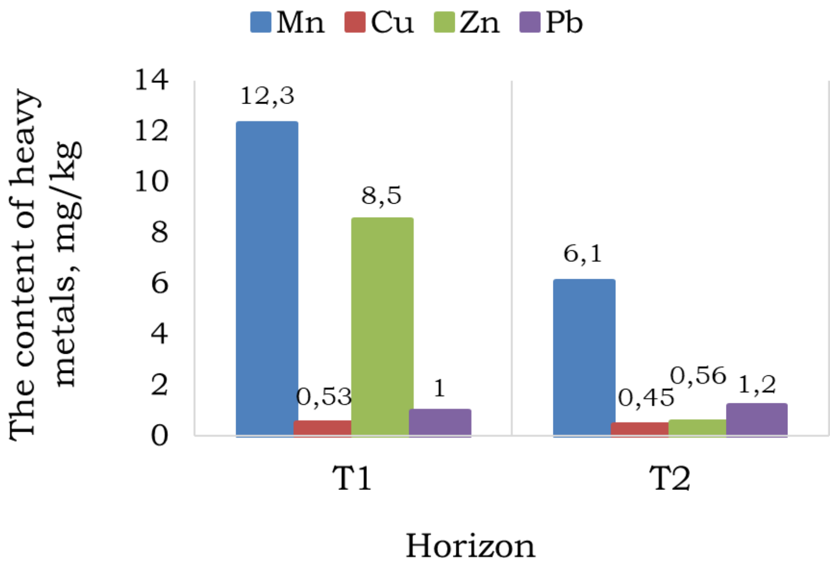

Figure 2. The content of manganese, copper, zinc, and lead in the studied horizons of section 1.

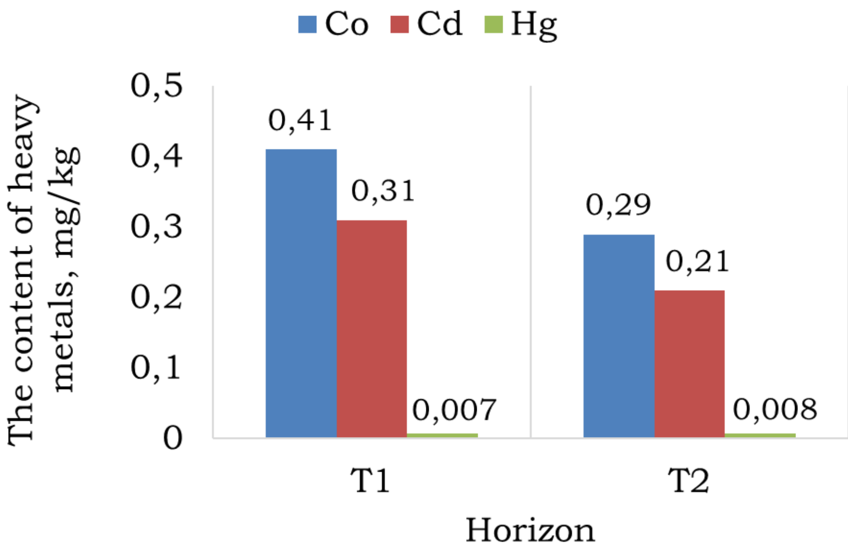

Figure 3. Content of cobalt, cadmium and mercury in the studied horizons of section 1.

and a low content of humus (2.06%) and nitrogen fertilizers (0.84 mg/100 g). In terms of humus, the peatland is considered like weakly humus.

When adding peat to the soil, it is necessary to improve agrophysical properties, since peat is depleted in nutrients. Effective use of peat for the development of agricultural crops is possible when fertilizers are applied to it.

The analysis of the micromycete activity of landfills showed that the families *Mucoraceae, Moniliaceae*, and *Tuberculariaceae* are widespread in the T1 horizon of the peatland. The total number of micromycetes was determined by sowing on Chapek's acidified nutrient medium (the number of colony-forming units – CFU in g of soil). This indicator turned out to be quite low compared to the background values. In general, all soils are characterized as very poor in the degree of micromycetes distribution.

10 species of micromycetes were found in soil profile No. 1. Among them are representatives

of the following families: *Mucoraceae* – 1 pc.; *Moniliaceae* – 5 pcs.; *Tuberculariaceae* – 4 pcs.

It should be noted that the presence of micromycetes of the genus *Fusarium* in the edaphotope indicates a significant content of mineral substances and a low content of heavy metals. This genus of micromycetes was discovered by researchers in landfill leachate during the study of a biosorption multilayer filter. Micromycetes of the genus *Fusarium*, along with bacteria, took an active part in the formation of the filter biofilm.

The analysis of peatland micromycetes by growth rate showed that slow-growing micromycetes have the largest share – 70%, respectively, fast-growing – 30%. Undoubtedly, such an indicator of the growth rate of mushrooms is negative, as it causes inhibition of the development of successional processes. The distribution by color showed that dark-colored micromycetes of the *Moniliaceae* family predominate and are characterized as toxic (80%), the share of light-colored ones is 10%, unclassified – 10%.

3.2. Genetic soil horizon No. 2

When describing soil profile No. 2, it was found that the soil is sod, shallow, light loamy, and glazed. The profile is made on the western side of the Lviv landfill at a distance of 20 m from the road that leads to the village Zbyranka. The soil-forming and underlying rock is loess loam. Genetic horizons H(gl) and P(h)(gl) were revealed.

It was established that the mobile forms of such heavy metals as Mn, Cu, Zn, and Pb do not exceed the maximum permissible concentration (MPC) and accumulate in the upper horizon. Exceeding the MPC is observed only for lead (2 mg/kg) in the H(gl) horizon. At a depth of 30 cm or more, the concentration of these elements decreases 10 times (figure 4).

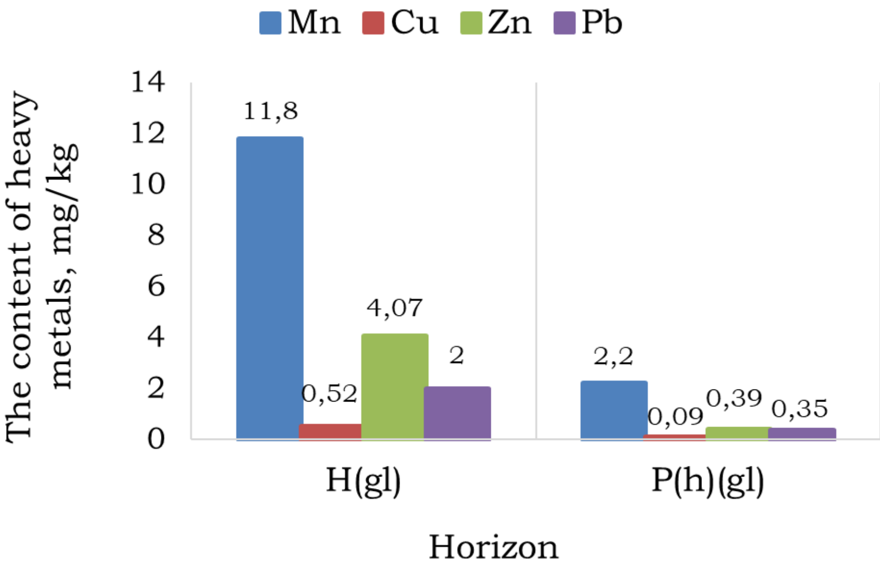

Figure 4. The content of manganese, copper, zinc, and lead in the studied horizons of profile 2.

Mobile forms of pollutants such as Co, Cd, and Hg accumulate, mostly, in the P(h)(gl) horizon of profile No. 2, but their content does not exceed the MPC (figure 5).

The mineral composition of the genetic horizons of soil profile No. 2 has quite high indicators, with the exception of humus, with content of 1.53-1.7%. According to this indicator, the soil belongs to low-humus, which is a disadvantage for the development of vegetation in the impact zone of the landfill. The content of NO_3 in the horizon is 20.6-30.5 mg/100 g of soil, P_2O_5 – 9.92-11.51 mg/100 g of soil, K_2O – 55.8-56 mg/100 g of soil (figure 6).

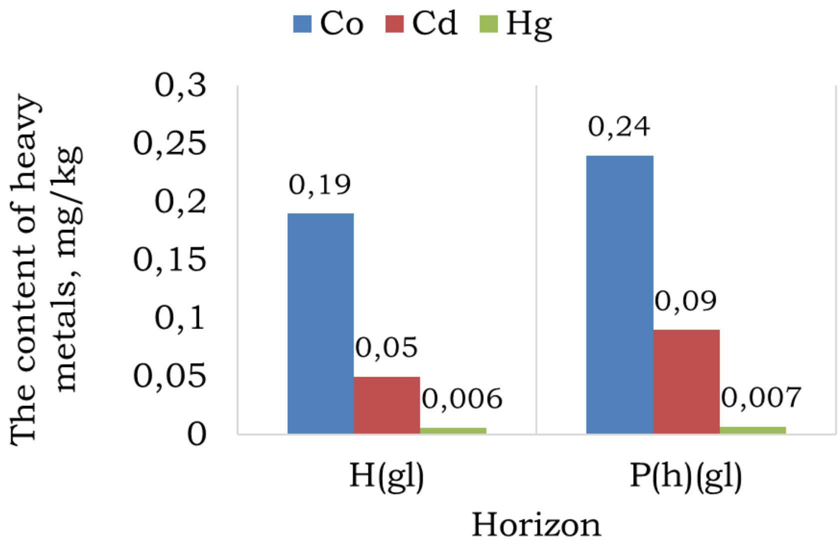

Figure 5. Content of cobalt, cadmium, and mercury in the studied horizons of profile 2.

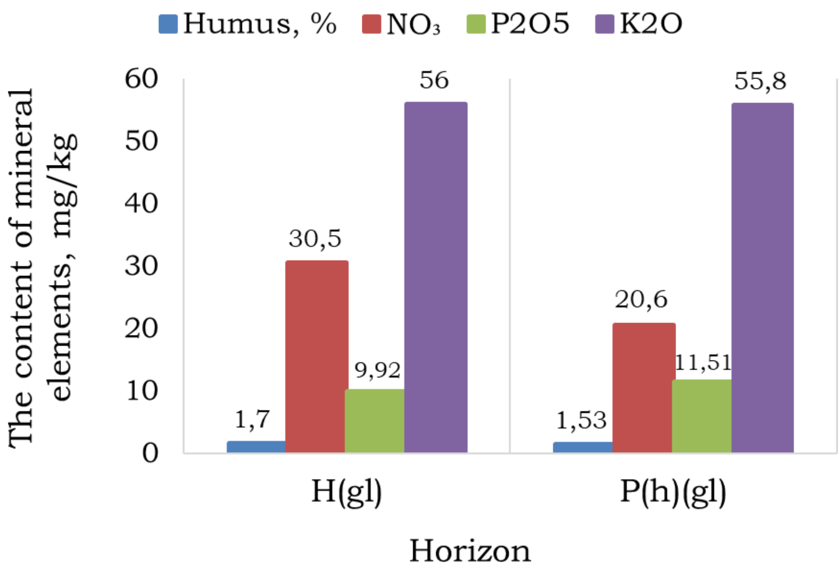

Figure 6. The content of mineral elements in the horizons of profile 2.

Thus, the soil located on the western side of the landfill did not tend to accumulate heavy metals, the concentration of which would exceed the MPC. However, the humus content in these soils is low, worsening the conditions for the syngenetic stages of succession.

The species composition of the micromycetes of the genetic horizons of the profile differs. Micromycetes of the *Mucoraceae, Moniliaceae* families develop in the H(gl) horizon. The P(h)(gl) horizon is inhabited by *Moniliaceae, Tuberculariaceae,* and *Dematiaceae.*

The life activity of the micromycete *Rhizopus stolonifer* (bread mold) in the upper horizon of the profile indicates their active participation in the syngenesis and decomposition of litter and leaf litter. These micromycetes develop on bread, fruits, and vegetables. It is well-known that microscopic fungi *Rhizopus stolonifer* can cause an allergic condition in humans. Micromycetes of the genus *Aspergillus* acquired the greatest development in this soil. These microfungi are involved in the transformation of organic matter and plant residues. In general, the micromycete species composition of the profile is extremely depleted, and the abundance of the species composition is low.

One of the most opportunistic and toxin-producing micromycetes is *Aspergillus fumigatus* Fries.var.sclerotiorum, discovered by us in this soil profile. This micromycete can cause mycosis and mycotoxicosis in living organisms (humans, animals). On figure 7 is shown a micromycete under a microscope.

Analysis of micromycetes by color and growth rate showed that dark-colored (78%) and slow-growing (89%) micromycetes develop within this genetic horizon. The rates of slow growth are even higher than for the peatland, indicating the detrimental effect of the hazardous factors of the landfill on micromycetes, including heavy metals and radionuclides. The share of fast-growing micromycetes is 11%, light-colored – 11%, and unclassified – 11%.

3.3. Genetic soil horizon No. 3

The studies of turf soil (profile No. 3), formed in conditions of moistening of the territory, showed that it has slightly different physical and chemical parameters. The name of the soil (with mechanical composition) is the field: sod, deep, clay, medium loam (light).

It was formed on diluvial sediments. The cut is laid 100 m east of the foot of the landfill and

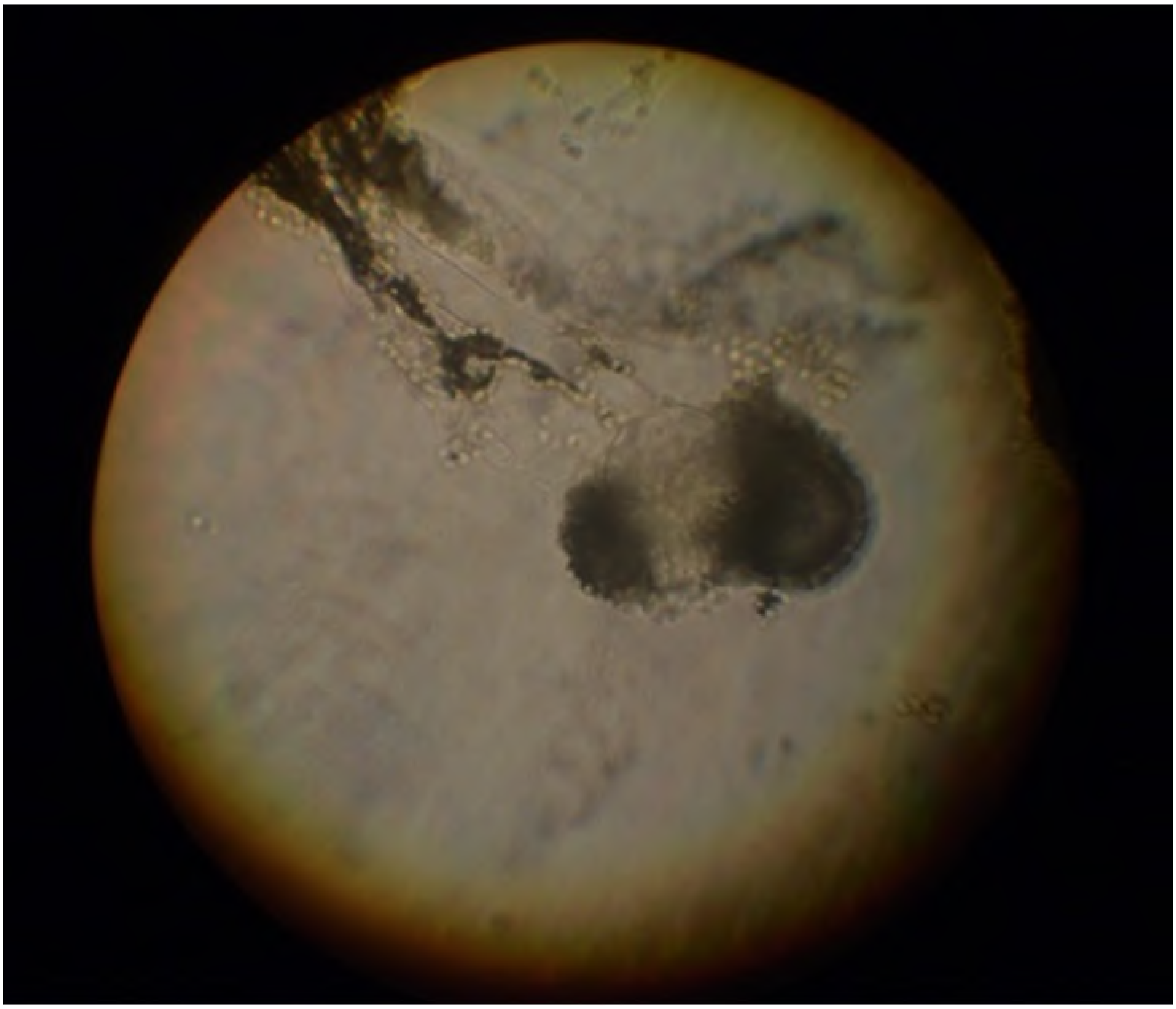

Figure 7. *Aspergillus fumigatus* Fries.var.sclerotiorum.

70 m perpendicular to the road that leads to it. Such genetic horizons as H(o), H, H(p)(gl), P(h)(gl) were identified.

The content of mobile forms of Mn and Cu increases with depth (from 29.4 mg/kg to 39.7 for Mn and from 0.57 mg/kg to 0.93 mg/kg for Cu), however, they do not exceed the MPC. The content of Zn in genetic horizons is 1.6-3.9 mg/kg and also does not exceed the MPC. The content of Pb in the genetic horizons exceeds the MPC by 1.5 times and the concentration increases with depth starting from the level of 23 cm (figure 8).

Concentrations of mobile forms of Co, Cd, and Hg increase with depth but do not exceed the MPC. The accumulation of heavy metals in the genetic horizon P(h)(gl) indicates their leaching to the parent rock (figure 9).

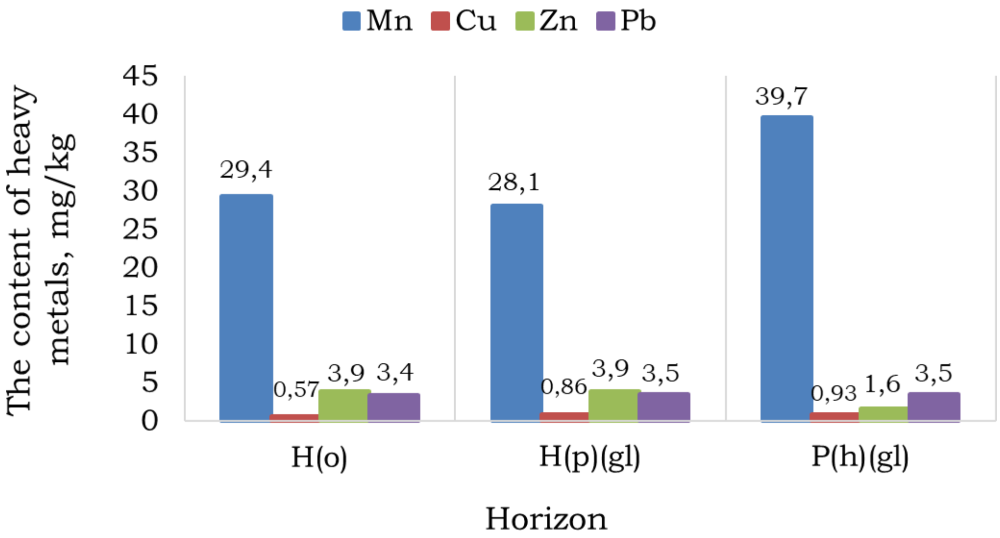

Figure 8. The content of manganese, copper, zinc, and lead in the investigated horizons of profile 3.

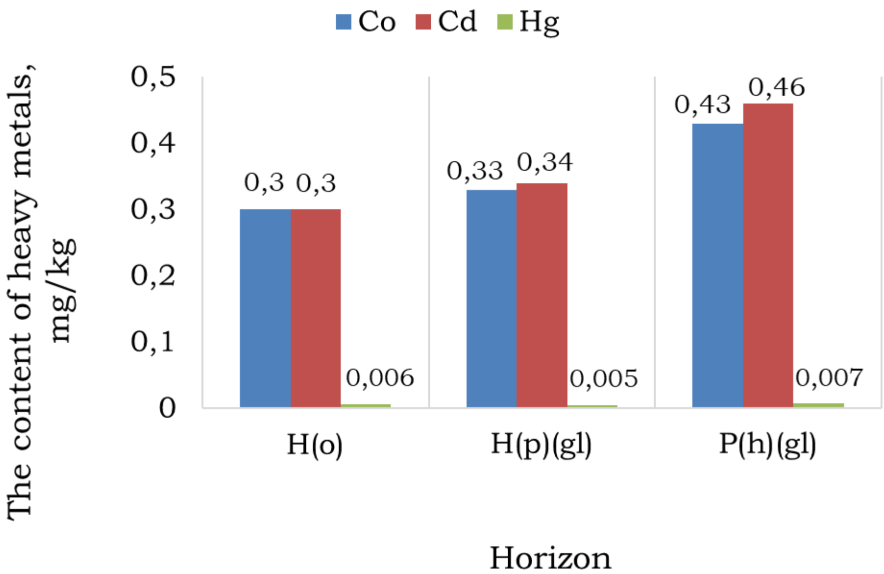

Figure 9. The content of cobalt, cadmium, and mercury in the studied horizons of profile 3.

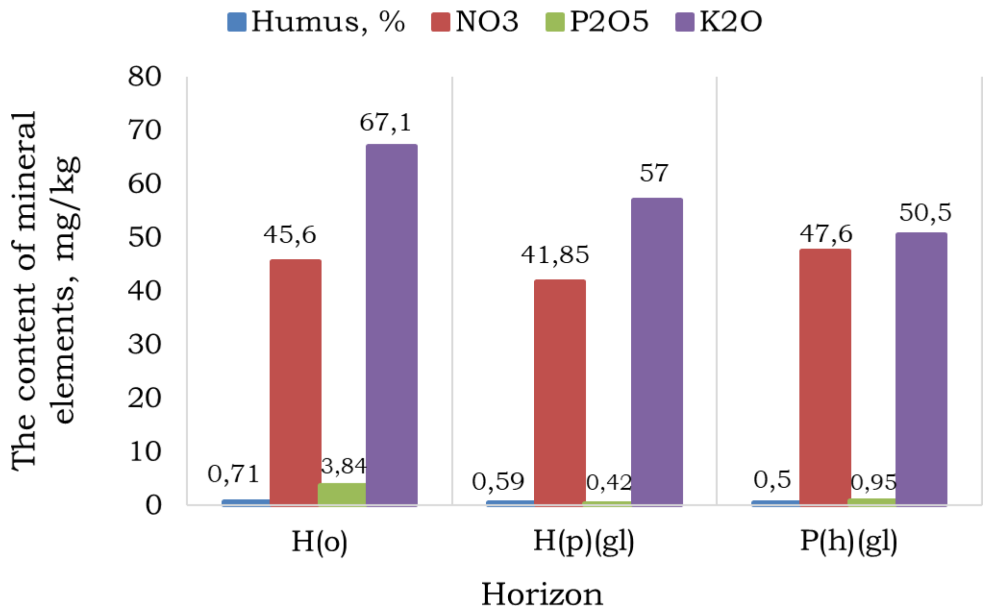

Figure 10. The content of mineral elements in the studied horizons of profile 3.

The humus content in the horizons decreases with depth and is only 0.5-0.71%. There is also a low content of P_2O_5 – 0.95-3.84 mg/100 g of soil and a decrease in concentration with depth. The concentrations of NO_3 and K_2O in the horizons are relatively high ranging from 41.85 to 47.4 mg/100 g of soil for the former, and from 50.5 to 67.1 mg/100 g of soil for the latter (figure 10).

Data on the content of heavy metals and the mineral composition of soil profile No. 3 make it possible to assert the negative impact of landfills on the adjacent territories and the environment. The concentrating of toxic elements with depth indicates their leaching to lower horizons and parent rock, which causes long-term technogenic pressing in the impact zone of landfills.

The species composition of micromycetes in section No. 3 is extremely depleted. A total of 10 species belonging to 3 families of the class *Hyphomycetes (Deuteromycetes)* were found.

The above data indicate the biological activity of micromycetes only in the upper layer of the horizon. Species *(Moniliaceae)* that carry out transformation reactions of complex organic compounds (solid and liquid paraffins, alcohols, diesel fuel, steroids) became the most widespread here. With depth (23-43 cm), the species composition and number of colonies decrease sharply, which indicates the contamination of the edaphotope with heavy metals, in the particular lead. At a depth of 43 cm and below, the vital activity of only one species is observed – *Mycelia st. dark*.

Analysis of micromycetes by color and growth rate of soil profile No. 3 showed that within this genetic horizon, dark-colored micromycetes develop the most (60%), light-colored micromycetes – 30%, unclassified – 10%. According to growth classification, only slowly growing micromycetes (100%) develop. The absence of any type of fast-growing micromycetes indicates strong pollution of the horizon with dangerous substances and compounds.

4. Conclusions

The conducted research and the results of analytical work in the laboratory showed that in the areas adjacent to the Lviv city landfill, mostly wet soils are common. The reason for their formation is insufficient drainage of the territory, which causes waterlogging in the area. Turf soils and peatlands were found.

When describing the genetic horizons of three profiles that are in the impact zone of the landfill, it was established that the content of heavy metals does not exceed the MPC, except for lead. The soil at the foot of the landfill turned out to be the most contaminated with heavy metals (profile No. 3). Also, the lowest activity of micromycetes was found in this soil.

The families *Mucoraceae, Moniliaceae,* and *Tuberculariaceae* are widespread in the T1 horizon of the peatland (profile No. 1). The presence of micromycetes of the genus *Fusarium* in the horizon proves a significant content of mineral substances and a low content of heavy metals. The species composition of the micromycetes of the genetic horizons of profile No. 2 is significantly different. Micromycetes of the *Mucoraceae*, and *Moniliaceae* families develop in the H(gl) horizon. The P(h)(gl) horizon is inhabited by *Moniliaceae, Tuberculariaceae,* and *Dematiaceae*. The species composition of micromycetes in profile No. 3 is extremely depleted. A total of 10 species belonging to 3 families of the class *Hyphomycetes (Deuteromycetes)* were found. With depth (23-43 cm), the species composition and number of colonies decrease sharply, which indicates the contamination of the edaphotope with heavy metals, in the particular lead. At a depth of 43 cm and below, the vital activity of only one species is observed – *Mycelia st. dark*.

It was found that the mobile forms of such heavy metals as Mn, Cu, Zn, Pb do not exceed the maximum permissible concentrations (MPC) and accumulate in the upper horizon No. 2. Exceedance of the MPC is observed only for lead (2 mg/kg) in the H(gl) horizon.

All soils in the area affected by the landfill are characterized as very poor in micromycete distribution. The taxonomic composition of mycelial fungi and the ecological and biological characteristics of the identified species indicate significant pollution of the ecosystem by household waste.

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References

[1] Uzbek I and Halahan T 2004 *Soil science* **5**(1-2) 102–106
[2] Sokhanchak R R and Lobachevska O V 2012 *Studia Biologica* **6**(1) 101–108 URL https://doi.org/10.30970/sbi.0601.197
[3] Oziegbe O, Oluduro A O, Oziegbe E J, Ahuekwe E F and Olorunsola S J 2021 *Saudi Journal of Biological Sciences* **28**(7) 3948–3956 ISSN 1319-562X URL https://doi.org/10.1016/j.sjbs.2021.03.072
[4] Andreyuk E I and Valagurova O V 1992 *Fundamentals of the ecology of soil microorganisms* (Naukova dumka)
[5] Ellis M B 1971 *Dematiaceous hyphomycetes* (Kew: Commonwealth Mycological Institute) URL https://archive.org/details/dematiaceoushyph0000elli
[6] Hassan A, Periathamby A, Ahmed A, Innocent O and Hamid F S 2020 *Journal of Soils and Sediments* **20**(1) 66–80 ISSN 1614-7480 URL https://doi.org/10.1007/s11368-019-02394-4
[7] Jia L, Zhou J, Cao J, Wu Z, Liu W and Yang C 2020 *Chemical Engineering and Processing - Process Intensification* **158** 108177 ISSN 0255-2701 URL https://doi.org/10.1016/j.cep.2020.108177
[8] Levik V 2009 *Biology and valeology* **11** 131–136
[9] Skrobala V, Popovych V and Pinder V 2020 *Mining of Mineral Deposits* **14**(2) 119–127 URL https://doi.org/10.33271/mining14.02.119
[10] Adamcová D, Radziemska M, Ridošková A, Bartoň S, Pelcová P, Elbl J, Kynický J, Brtnický M and Vaverková M D 2017 *Chemosphere* **185** 1011–1018 ISSN 0045-6535 URL https://doi.org/10.1016/j.chemosphere.2017.07.060
[11] Gautam M and Agrawal M 2019 *Applied Geochemistry* **104** 83–92 ISSN 0883-2927 URL https://doi.org/10.1016/j.apgeochem.2019.03.020
[12] 2022 State standard of Ukraine DSTU ISO 10390:2022 Soil, processed biowaste, and sediment. Determination of pH URL http://online.budstandart.com/ua/catalog/doc-page.html?id_doc=97744
[13] 2002 State standard of Ukraine DSTU 4114:2002 Soils. Determination of mobile compounds of phosphorus and potassium according to the modified Machyhin method URL http://online.budstandart.com/ua/catalog/doc-page.html?id_doc=58928

[14] 2005 State standard of Ukraine DSTU 4405:2005 Soil quality. Determination of mobile compounds of phosphorus and potassium by the Kirsanov method in the modification of the NSC ISA URL `http://online.budstandart.com/ua/catalog/doc-page.html?id_doc=60252`
[15] 2007 State standard of Ukraine DSTU 4770.8:2007 Soil quality. Determination of the content of mobile chromium compounds in the soil in a buffered ammonium-acetate extract with pH 4.8 by the method of atomic absorption spectrophotometry URL `http://online.budstandart.com/ua/catalog/doc-page.html?id_doc=91345`
[16] Dudka I A, Wasser S P and Ellanskaya I A 1982 *Methods of experimental mycology* (Naukova Dumka)
[17] A D, Oka M, Fujii Y, Soda S, Ishigaki T, Machimura T and Ike M 2017 *Science of The Total Environment* **584-585** 742–750 ISSN 0048-9697 URL `https://doi.org/10.1016/j.scitotenv.2017.01.112`
[18] Suchecka T, Lisowski W, Czykwin R and Piatkiewicz W 2006 *Filtration & Separation* **43**(5) 34–38 ISSN 0015-1882 URL `https://doi.org/10.1016/S0015-1882(06)70891-6`
[19] Renou S, Givaudan J, Poulain S, Dirassouyan F and Moulin P 2008 *Journal of Hazardous Materials* **150**(3) 468–493 ISSN 0304-3894 URL `https://doi.org/10.1016/j.jhazmat.2007.09.077`
[20] Malovanyy M, Moroz O, Popovich V, Kopiy M, Tymchuk I, Sereda A, Krusir G and Soloviy C 2021 *Environmental Nanotechnology, Monitoring & Management* **16** 100611 ISSN 2215-1532 URL `https://doi.org/10.1016/j.enmm.2021.100611`

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The management of transformed small river basins of Volyn Polissia – Buniv River case study

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Abstract. The assessment of the transformation level in the Buniv River basin (Ukraine) transformation was performed. Substantiates the need to improve the monitoring system within the river basin, as the main tool for assessing and predicting changes in the aquatic ecosystem and managing the processes of its anthropogenic. The research methods included on-site investigations, laboratory and analytical studies, data processing using GIS technologies. A topographic survey of the Buniv River's floodplain within the village of Rokytne town was performed. The on-site investigations included field surveys and water sampling at 4 control sites on the Buniv River for 13 quality indicators. The analysis of the obtained cartographic models indicates a significant anthropogenic transformation of the natural landscapes. A significant part of the watercourses of the Buniv River basin was once directed and transformed into main canals of the meliorative systems. This causes the formation more dangerous flood flow.

1. Introduction

The current national environmental policy of Ukraine in the field of water management is aimed at the Implementation of the Water Framework Directive 2000/60/EC (EFWD) [1] on ensuring sustainable resource management, meaning the European Model of Water Resources Management. The EFWD aims to protect and improve the state of water resources and promote their sustainable and balanced usage. It sets out the basic provisions for EU countries to achieve good surface, ground, transitional and coastal waters within each river basin. In order to implement the EU's directives on river basin protection, the Verkhovna Rada of Ukraine preserved the integrated approach to water resources management based on the basin principle at the legislative level. For this, they adopted in 2016 under No. 1641 – VIII the Law of Ukraine "On the modification of some legislative acts concerning the introduction of integrated approaches in the water resources management by the basin principle"; on 26.10.2017 under No. 25 the Order of the Ministry of Environment "On the allocation of sub-basins and water management areas within the established areas of river basins"; on September 19, 2018, under No. 758 the Resolution of the Cabinet of Ministers of Ukraine "On approval of the procedure for state water monitoring," etc.

The above-mentioned law and bylaws are aimed at implementing a system of integrated water resources management based on the basin principle by:

- Developing and adjusting the river basin management plans
- Developing the water management balance sheet;
- Determining the hydroecological state of the surface waters.
- Determining the powers of the central and local authorities, local self-government bodies in the implementation of water protection measures, etc.

In addition to this, the relevant State Agency for Water Resources of Ukraine is committed to developing the river basin management plans for 9 river basin districts. As of today, the water massifs and the typology of the general hydrographic network of Ukraine have been identified; the diagnostic and operational monitoring of the transformed surface water massifs has been carried out, and the reference conditions of the river basins have been established.

Also, in 2021, plans were made to complete the works on creating classifications of the ecological state of water bodies, establishing their ecological and chemical states, as well as determining ecological purposes for these water bodies.

Volyn Polissia is transboundary region. At the same time, Ukraine has committed itself to implement the Convention on the Protection and Use of Transboundary Watercourses and International Lakes (Convention on Transboundary Waters) [2]. The main purpose of this Convention is to approve the measures to protect and ensure the quantity, quality and sustainable usage of both surface and underground transboundary water resources at the local, national and cross-border levels. Within the Convention, the industry institutions should apply an integrated basin approach based on the understanding that water resources are an integral part of the ecosystem and play a crucial role in the socio-ecological and economic development of territories.

The Convention requires the states to fulfill certain obligations: to control and reduce the negative transboundary impacts on the hydroecosystems and river basin territories at the different levels; to apply an ecosystem approach in the field of common water resources management in compliance with the principles of “polluter pays”, “cautiousness”; the conservation and the restoration of ecosystems; to implement environmental impact assessments; to set common goals to achieve a “good state” of water quality, monitoring the state of transboundary rivers; to minimize man-made risks, etc.

Therefore, today, in our opinion, it is extremely important to develop and implement a joint program for monitoring rivers and to apply a common tested and approved methodology for effective integrated water resource management of the transformed rivers. This includes the assessment of the ecological state of river basins using GIS technologies; determining the environmental goals to achieve a “good state” of water quality; developing compensatory water protection measures; developing the design and estimate documentation if necessary; the organizational tools for attracting water users, all interested parties, state authorities, and local self-government bodies, etc. Along with these important and topical issues is the need to ensure the flood safety of riverine territories of the Polissia zone, as well as adapting to climate changes.

This is exactly the problem that arose in the basins of small rivers in the border areas of Volyn Polissia after the flood on May 17, 2018. Then, as a result of great precipitation, there was a rapid rise in water levels, which led to the flooding of residential buildings, including the threat of the destruction of the pressure front structures at the recreational reservoir in the Rokytne town (Rokytne), Rivne region [3]. The heavy rain on May 16, 2018, which lasted about 10 hours, led to the flooding of 378 households located on the border territories of the Sarny district in the Rivne region, as well as the different infrastructure facilities. The most affected locations were those belonging to the basin of the Buniv River (a tributary of the Lva River).

Therefore, today it is important to use methodological approaches to protect, preserve and restore the surface waters of the Buniv River basin, which is the goal of our work.

This research is devoted to developing the methodology elements for managing transformed basins of the small rivers at the border part of Volyn Polissia, substantiating technological solutions for the restoration and protection of the surface waters, which were tested on the example of the Buniv River basin.

In order to achieve the set **goal**, the following **tasks** were performed: on-site investigations and instrumental studies of the Buniv River basin were carried out; the ecological stability of the landscape and hydrological and morphological features of the river were assessed; the quality of the river's surface water and bottom deposits were assessed; management solutions were developed to achieve a "good state" of surface water quality according to the requirements of the EU WFD, as well as to protect the territory from floodwaters.

This report is a study on the changes in the ecological state of the Buniv River basin. The indicators that characterize the quality of river surface water and the compensatory organizational and technical solutions for restoring the aquatic ecosystem are the subject of the study.

2. Brief literature review

The Volyn Polissia waterways, especially the small rivers, are exposed to significant anthropogenic pressure [4–7]. The quality of the surface water does not meet the requirements of the EU Water Framework Directive, and their current state is assessed as critical [8]. In the border areas of Volyn Polissia, small rivers with their swampy catchment area and preserved forest vegetation form the water content, hydrochemical regime, hydroecological state and water quality of the basins of medium and large tributaries of the Prypiat. Unfortunately, the majority of rivers have been diverted, become shallow, and are affected by the pollution from diffuse and point wastewaters from industrial enterprises, agricultural production, utilities, etc.

A significant role in the destruction of the ecological situation in these river basins is played by non-compliance with the requirements of water legislation (Water Code of Ukraine) [9], deforestation, the "chemization" of agriculture, creating and functioning a cascade of ponds and reservoirs, violating the rules of operation in water bodies, violating the mechanisms of hydraulic structures (cross regulators) that do not provide water passage during floods and inundations, the intensive use of water resources, the discharge of significant volumes of polluted water, etc. Such a powerful transformation of the territories [6] and water areas of river basins at the border territories in terms of the scale of manifestations and the impact intensity makes it necessary to find ways to optimize resource management, develop compensatory water protection measures (technological road map) and integrate water resources management in these transformed river basins of the border territories [4, 5].

Further delay in resolving this problem will lead to a decrease in the assimilation capacity of hydroecosystems of the Volyn Polissia river basins [10], and deterioration in the ecological situation of the main border artery, meaning the Pripyat River. For Ukraine and Belarus, resolving the above problems is extremely important, especially for the residents and water users living in the border areas that use surface water for various economic purposes.

3. Methods of factual analysis. Research area

The research methods included on-site investigations, laboratory and analytical studies, data processing using GIS technologies. A topographic survey of the Buniv River's floodplain within the village of Rokytne was performed. The on-site investigations included field surveys and water sampling at 4 control sites on the Buniv River for 13 quality indicators. A full-scale survey of individual sections of the river catchment area was carried out using an unmanned aerial vehicle. The chemical and analytical quality control of the Buniv River's surface waters was carried out according to regulatory requirements in the certified laboratory of water quality at the National University of Water and Environmental Engineering in Rivne city. The instrumental studies (dissolved oxygen content, oxygen saturation temperature, pH, ox-redox potential) were determined at the sampling site using certified mobile devices, the EZODO 7031 and Adva AD 11.

The procedure for sampling water at the Buniv River for hydrochemical analysis was carried out according to the relevant state standards:

- GOST 17.1.5.05 – 85 General requirements for sampling surface and sea waters, ice and atmospheric precipitation // State Committee of the USSR on standards;
- DSTU ISO 5667-1: 2003 – Water quality. Sampling. Part 1. Instructions on the draft programs for sampling // Order No. 102 of the State Consumer Standard Service of June 11, 2003;
- DSTU ISO 5667-6: 2009 Water quality. Sampling. Part 6. Guidelines for sampling from rivers and streams (ISO 5667-6: 2005, IDT);
- Methodological guidelines "Sanitary and virological control of water objects" under article 40 of the Law of Ukraine "On ensuring sanitary and epidemiological welfare of the population" // Order of the Ministry of Health Care of Ukraine No. 284 of 30.05.2007.

Water sampling for analysis was carried out under conditions for the river's lowest water content (during the summer low water period) at daylight hours. The sampling control points (research area located on N 51.280588, E 27.218915) assumed representativeness according to the level of anthropogenic load: 1-st section of the Buniv River, 50 m below the railway bridge (point PK-21); 2-nd section – Buniv River, 250 m below the railway bridge (point PK 18); 3-rd section – Buniv River, reservoir (PK10); 4-th section – Buniv River, the reservoir (PK3) (figure 1).

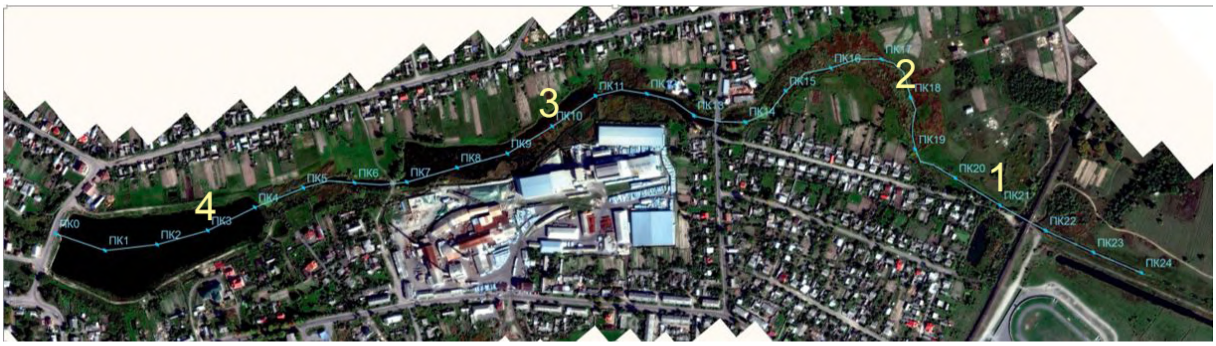


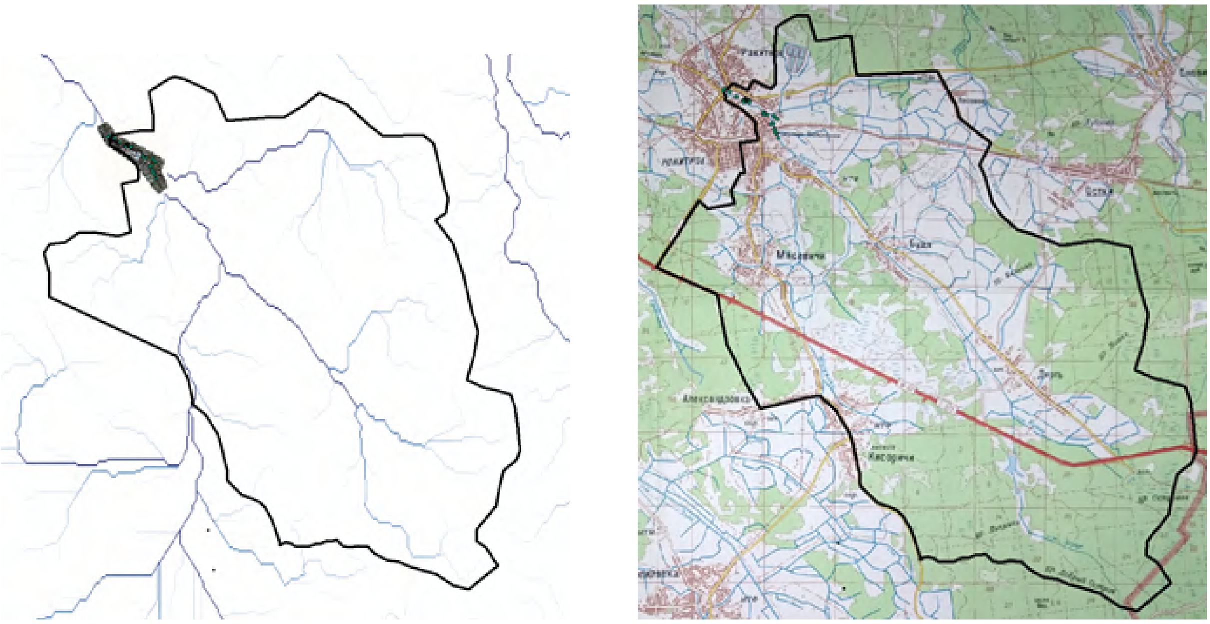
Figure 1. The sampling control points location (*marked in yellow*) and diagram of the survey route (*from PK0 to PK24*).

The assessment of the Buniv River basin's surface water quality was carried out in accordance with the method of "Comprehensive Expert Assessment of River Basin Ecosystems" (IE) [11].

Sampling bottom deposits was carried out under the standards (DSTU ISO 5667-12-2001 Water quality. Sampling. Part 12. Guidelines for sampling bottom deposits [ISO 5667-12:1995, IDT]) on a 50 x 50-meter grid with a clamshell and capture area of 0.1 m^2. Immediately after lifting the samples of bottom deposits, their field description was carried out. The mixed samples were used for further laboratory study and clarification with a lithological study of the bottom deposit composition. A total of 3 samples of bottom deposits in the Buniv River and 2 samples in the reservoirs were collected. For calculating the total pollution index we used the methods in force in Ukraine.

3.1. Description of the research area

The Buniv River basin is a typical small river of the border territory, located within the Sarny district of the Rivne region, a right tributary of the Lva river tributary (Pripyat river basin, 16-th ecoregion). The length of the river is 23 km, the slope of the river is 1.1 m/km. It is formed from many unnamed streams and reservoirs. The river has two main tributaries. An assessment of the Buniv River basin's territory was carried out based on remote sensing data (Sentinel 2, SRTM) and topographic maps (figure 2). As we can see, the catchment area obtained using DEM processing is not relevant to the actual real situation in south-western part (near villages Kysorychi and Masevychi). There, the network of drainage channels and regulation constructions has altered the conditions of flow accumulation. It's a good illustration of the necessity of using topographic maps for hydrological research within Volyn Polissia where similar constructions is widely spread.



(*a*) (*b*)

Figure 2. Setting catchment boundaries according to satellite data (*a*) and topographic map (*b*).

The analysis of the obtained cartographic models indicates a significant anthropogenic transformation of the natural landscapes. A significant part of the watercourses of the Buniv River basin was once directed and transformed into main canals of the meliorative systems (figure 3). As a result, the profile of the riverbed and its tortuosity have changed. The direction of the river's hydrographic network led to an increase in the slopes, carrying capacity, and speed of the flood wave.

Also, engineering surveys and a full-scale survey of the basin territory indicate that currently there is an increase in anthropogenic load on the river basin due to the overregulation of river flow, floodplain development, changes in morphological parameters, flooding of the territory, and so on. In our opinion, the changes in the structure and the water body's functioning parameters are a consequence of the manifestation of transformation and degradation processes that develop under the influence of natural and anthropogenic factors.

Today, the economic development of the catchment area is quite high. A significant percentage of the territory is located in residential areas; the floodplain of the river is disturbed and built

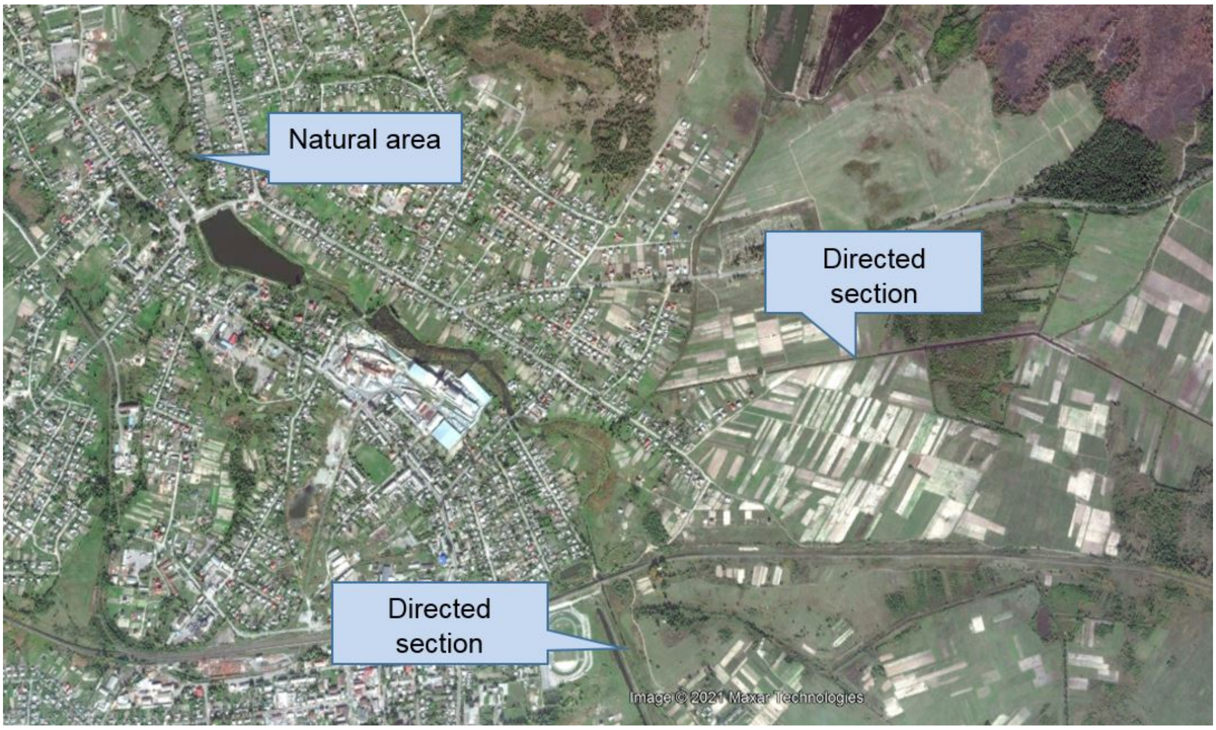


Figure 3. Typical natural and directed sections of the Buniv River hydrographic network (image source: Google Earth Pro).

up. Uncontrolled and untreated surface runoff flows from the residential areas to the Buniv River and, accordingly, to the reservoirs in Rokytne. Most often, these are formed after heavy rains or during the melting of snow cover. A significant part of the households at Rokytne are located in the floodplain of the river, in the zone of possible territory flooding during floods and inundations.

In general, the Buniv River basin chosen for the study is typical for the border part of Volyn Polissia. Its main features include a significant transformation of the natural hydrographic network into a system of ameliorative channels by straightening riverbeds; the presence of water-regulating structures that are not always in good condition; the significant drainage of wetlands; the insufficient carrying capacity of some bridge crossings; the active use of floodplains for residential development and economic activities; the insufficient density of the monitoring system for registering extreme precipitation in the small river basins.

These factors pose a danger to aquatic ecosystems, the population and engineering infrastructure of the border areas.

4. Results and discission

4.1. Hydrological and morphological assessment of the river

For evaluating the valley and riverbed transformation, and undertaking management decisions on the flood safety of territory planning, we performed a topographic survey of the Buniv riverbed and valley within the most affected part of Rokytne.

The analysis of the constructed longitudinal profile along the river axis (the diagram is shown in figure 1) allowed dividing the study into five sections, differing in their carrying capacity and passing conditions of the flood wave.

1. The section near the railway bridge (from PK 24 to PK 19) has a length of 500 m. The

average slope is 0.022%, rectilinear; it has ridge formations of bottom deposits with a length of 14..16 m. and a height of 0.3..0.4 m. This situation is typical for the Buniv River almost along its entire length. As a result, the first section has the appearance of the non-typical flat Polissia river (figure 2), and represents the principal channel. These transformations contribute to a shorter duration of water standing on the floodplain, but the floods become more pronounced with higher maximum costs. Thus, this section is estimated at a comparably high carrying and transport capacity, which intensely transfers water to the next section.

2. The next section further downstream (from PK 19 to PK 16+75), with a length of 300 m, is characterized by a conditionally undisturbed current; it has a formed meander, as a result of which the channel slope decreases by 30%, having an average slope of 0.013%. A decrease in the river's slope leads to a decrease in the flow rate, the ability to carry deposits, and, accordingly, an increase in water levels at the maximum flow rates.
3. Further, the riverbed (the section from PK16+75 to PK12.0 with a length of 475m) is under the influence of a bridge crossing. From the upper part, from PK16+75 to the bridge, the channel is positioned, due to the support of the stream by the river crossing. The water level on the site is close to the horizontal level and has a slope of 0.003%. A sharp drop in speed causes sediment deposits in this area during the decline of floods and inundations. In the future, shallow water will form on this site, additionally overgrown with higher aquatic vegetation. Further floods begin at higher bottom levels and, accordingly, at higher water levels. Below the bridge, there is an increase in the slope to 0.067%, a significant acceleration of the flow causing bottom erosion. This is due to the high rates of compressed flow coming out of the bridge opening.
4. The next section (from PK16+75 to PK 6+75) with a length of 1000 m is the surface of the enterprise's reservoir and has a zero hydraulic slope. For a long time, the reservoir was not operated according to the design modes. Instead of the normal headwater level mark at 171.25, which is provided for in the project, the mark of 170.70 m is kept. This is due to developments at the territory previously allocated for the reservoir. Due to the decreased depth, the reservoir is a shallow water area with developed higher aquatic vegetation. From the point of view of flood safety, the section is characterized by low carrying capacity due to the significant overgrowth of the riverbed with aquatic vegetation and almost zero hydraulic slope. In addition, it determines the operation of the stage opening on the PK 13+30 in the flooded spillway mode, which approximately by 10..15% reduces its carrying capacity.
5. The section of the next reservoir also has a zero hydraulic slope. In addition to the functionality of the culverts, the reservoir is in a good condition. The lack of proper regulation of water discharge affected the scale of flooding in Rokytne during the flood on 17.05.2019, figure 4 shows the impact of existing engineering infrastructure on the formation of flood zones. As can be seen, there is an excessive compression of the river flow, which causes the flooding of the river valley.

We have calculated the maximum flow rate through the opening of the road bridge on 8 Bereznia Street in Rokytne. (indicated by the arrow in figure 5) for the flood conditions on May 17, 2019, as for a spillway with a wide threshold of 26.6 m^3/s. This corresponds to a provision of 3%, that is, 1 time in 30 years; these floods can occur in the summer.

4.2. Proposed solutions
Operation of culverts

The lack of water level regulation at culverts during the May 17-19, 2019 flood caused a short-term overflow of water through the earthen dam. It has been established that the erosion of an earthen dam during the floods leads to a breakthrough and the formation of a wave with a

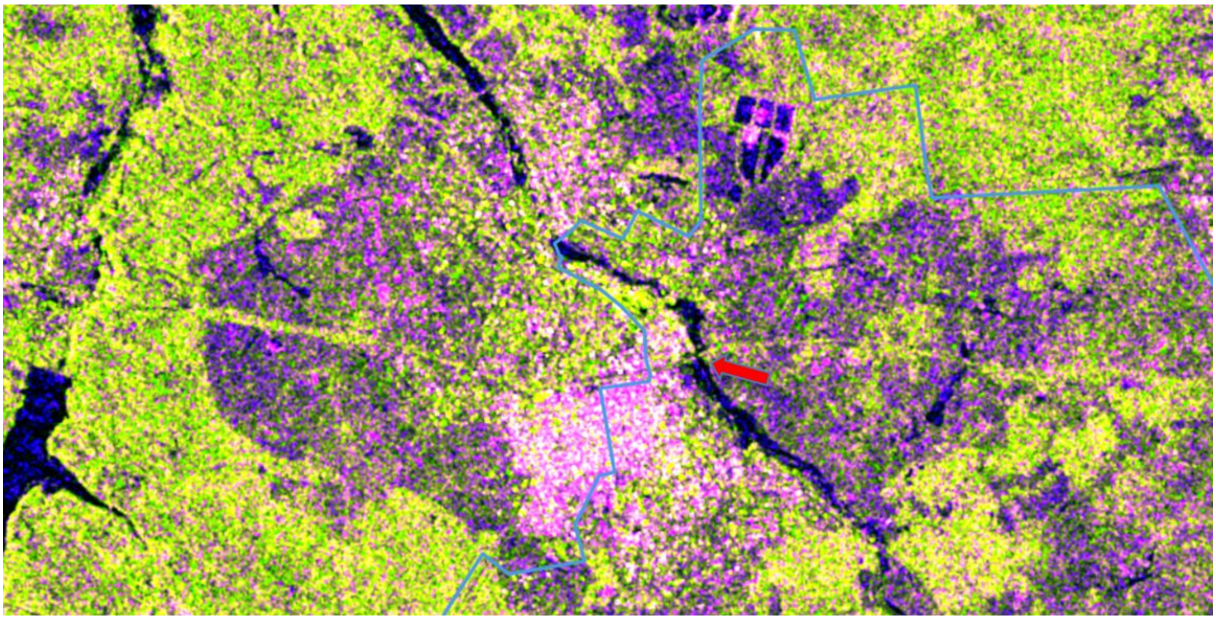


Figure 4. Fragment of the basin of Buniv River during the flooding on May 17, 2019 (model obtained using EOS Land Viewer).

great destructive force. This was prevented by the retention of a certain amount of water by the technical reservoir of the glass factory, as well as flooding of the floodplain above the automobile bridge.

In addition, the backup of water from this reservoir reduced the carrying capacity of the objects located upstream, which certainly contributed to a long stay of high water levels in the flooded areas.

Thus, a necessary condition for flood management is the development and implementation of a reservoir management plan depending on the meteorological situation in the river basin.

Technical capabilities of flood runoff redistribution

The technical capabilities for delaying this volume at the Buniv River's catchment area above Rokytne will allow floods in the banks of the river to pass through the village. However, the possible regulation of runoff should still include the release of water into the floodplain, as this is an important component of maintaining the ecosystem and the river water quality.

It should be noted that it is unlikely to find such opportunities without allocating land plots for polders or reservoirs. We estimated the flood volume to be 3.45 million m^3. In order to retain this amount of water within the Buniv River's tributaries, it needs to have a total length of about 700 km. The river basin does not have such a developed hydrographic network. This approach also requires a significant number of regulatory structures at individual channels.

A technically possible method is to transfer part of the flood runoff (figure 5) from the Buniv River to the Lva River (above the villages of Masevychi, Buda) and the Berest River (in front of Rokytne and near Lisove village).

To do this, it is necessary to arrange either appropriate cross regulators, or lay pipeline structures that have a carrying capacity at a safe level for Rokytne's flow rates, whose value shall be determined by calculation. The economic feasibility of this type of construction should be justified by the agricultural, flood control and other needs and costs for their maintenance.

According to DSTU 7369:2013, the bottom deposits of the Buniv River belong to Group 1 of

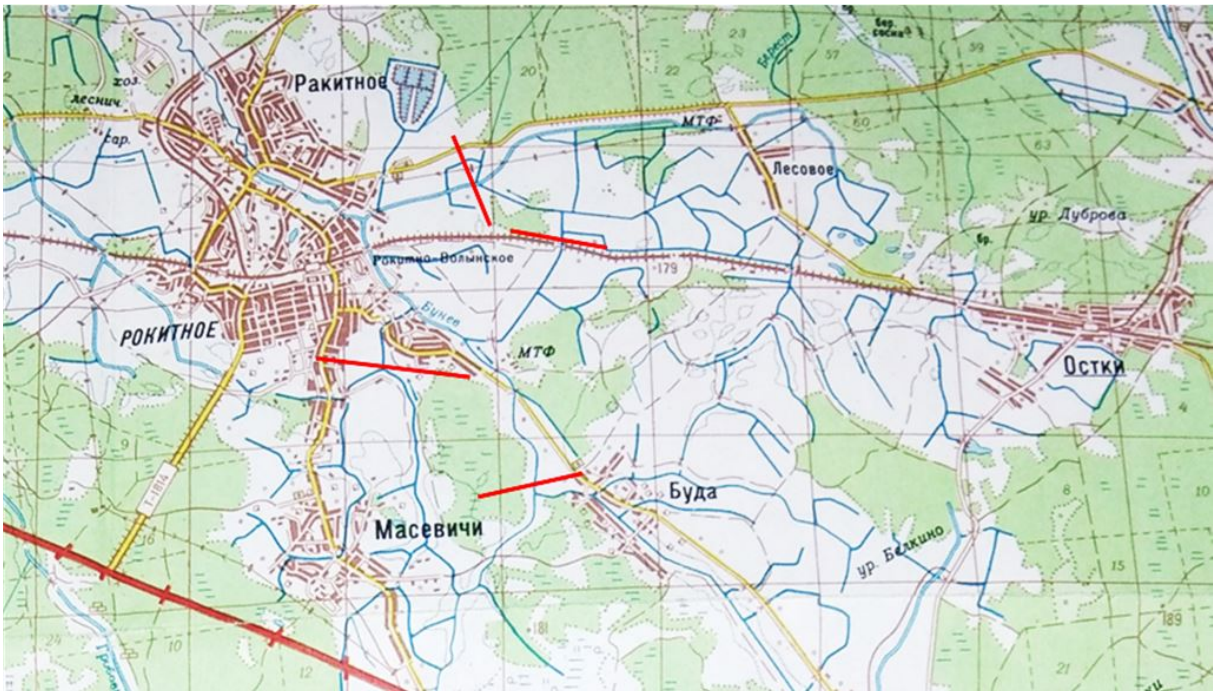


Figure 5. Creating a possible redistribution of flood runoff.

the group's classification for the permissible values of heavy metals in the deposits. Regarding the maximum permissible concentrations (MPC) of chemical elements in the soil, an excess content in the bottom deposits of the Buniv River was observed only for Co, averaging 1.6 times at the cross-section, and Cd averaging 2.3 times at the cross-section. High levels of heavy metals in water or other media have a toxic effect, and the accumulation of such elements in the tissues of hydrobionts causes a violation of biochemical processes and physiological functions.

4.3. Limnological surveys

The analysis results of the chemical element content in the bottom deposits of the studied section (table 1) indicate the presence of all six studied elements.

Table 1. Chemical composition of the bottom deposits of the Buniv reservoir.

Cross-section No.	Indicators						
	Cs137, Ci/km^2	Cu	Zn	Mn (mg/kg)	Co	Cd	Pb
1	0.017	2.25	17.4	234.8	6.1	1.3	13.0
2	0.016	2.21	4.00	237.4	5.7	1.4	15.1
3	0.018	2.86	4.25	251.6	5.9	1.3	14.8
4	0.003	2.18	5.10	197.2	5.3	1.7	14.6

The source of anthropogenic entry of heavy metals into water bodies is primarily associated with road transport and wastewater, including natural causes such as the decomposition of dead hydrobionts.

4.4. Hydrochemical assessment of the Buniv River's surface water quality

The surface water quality of the river was assessed using the main hydrochemical indicators, which are crucial in the formation of the surface water quality of Volyn Polissia's typical rivers. The summary results of the Buniv River surface water quality assessment, namely, the actual concentrations of biogenic substances, the multiplicity of exceeding environmental standards and the degree of surface water pollution are presented in table 2.

Ammonium and nitrogen ammonium. The concentration of ammonium in water bodies for domestic use should not exceed 2 mg N/dm^3 by nitrogen. MPC$_{fishfarm}$ of ammonium salt is 0.5 mg N/dm^3 (by nitrogen) (this limiting indicator of harmfulness is toxicological). According to European standards, the concentration of ammonium in recreational reservoirs should not exceed 0.1 mg NH_4/dm^3.

The presence of ammonium ions is mainly associated with the processes of biochemical degradation of the protein substances, deamination of amino acids, and decomposition of urea under the urease action. The content of ammonium ions in natural waters varies from 12 to 205 mg N/dm^3 in terms of nitrogen. During the transition from oligotrophic to meso – and eutrophic reservoirs, both the absolute concentration of ammonium ions and their share in the total balance of bound nitrogen increase.

The presence of ammonium in concentrations near 1 mg/dm^3 reduces the ability of fish hemoglobin to bind oxygen. The signs of intoxication are disturbances, convulsions, the fish throws itself on the water and jumps to the surface. The mechanism of toxic action is a violation of the central nervous system, damaging the gill epithelium, hemolysis (rupture) of the red blood cells. The toxicity of ammonium increases with increasing pH medium. The increased concentration of ammonium ions can be used as an indicator that reflects the deterioration of the sanitary condition of a water body, the process of contamination of the surface and underground waters, primarily by domestic and agricultural effluents.

Nitrites and nitrite nitrogen. For nitrites, the MPC$_{household}$ is set at 3.3 mg/dm^3 as an ion of NO_2^- or 1 mg/dm^3 in terms of nitrogen. The MPC$_{fishfarm}$ is 0.08 mg/dm^3 as an ion of N_2^- or 0.02 mg/dm^3 in terms of nitrogen. According to European standards, the concentration of nitrites in recreational reservoirs should not exceed 0.03 mgN_2^-/dm^3.

Nitrites are dissolved in surface waters. The acidic waters may contain small concentrations of nitric acid (HNO_2^-) (not dissociated into ions). The increased content of nitrites in the Buniv River indicates an increase in the decomposition of organic substances under conditions of slower oxidation of NO_2^- into NO_3-, which indicates the contamination of the water body.

Nitrates and nitrate nitrogen. The MPC$_{household}$ for nitrates is 45 mg/dm^3, or 10.0 mg/dm^3 (for nitrogen) and the MPC$_{fishfarm}$ is 40 mg/dm^3 (by NO_3-) or 9.1 mg/dm^3 (by nitrogen). According to European standards, the concentration of nitrates in recreational reservoirs should not exceed 5.0 mg NO_2^-/dm^3. The presence of ammonium nitrate in concentrations of up to 2 mg/dm^3 does not cause a violation of biochemical processes in a reservoir; the maximum concentration of this substance, which does not affect the sanitary regime of the reservoir, is 10 mg/dm^3. The harmful concentrations of nitrogen compounds (primarily ammonium) for various fish species are on the order of hundreds of milligrams per 1 dm^3 of water.

Phosphates. The MPC$_{household}$ for phosphates is 3.5 mg $PO_4{}^{2-}$/dm^3, the MPC$_{fishfarm}$ is 0.05 mg $PO_4{}^{2-}$/dm^3.

According to European standards, the concentration of phosphates in recreational reservoirs should not exceed 0.2 mg of $PO_4{}^{2-}$/dm^3. The excessive phosphorus compounds from various sources such as mineral fertilizers, untreated domestic wastewater, and industrial waste are being carried by surface runoff from fields into the river. This inflow causes significant growth in the water body's plant biomass. As the concentration of phosphorus in the water increases, it changes the trophic status of the reservoir, leading to a restructuring of the entire water community. This restructuring results in the prevalence of putrefactive processes, leading to

Table 2. The Buniv River's surface water quality assessment.

Control point	Actual content, mg/dm^3	Multiplicity of exceeding			Water quality category	Contamination level
		fish farm norms	household norms	Directive 76/160/EC		
			by nitrites content			
1	0.490	8.4	0.2	–	4.8	Dirty – very dirty
2	0.045	0.6	0.0	–	4.7	Moderately polluted
3	0.066	1.0	0.0	–	6.5	Dirty- very dirty
4	0.044	2.4	0.1	–	4.5	Moderately polluted
			by nitrite nitrogen content			
1	0.180	10.0	0.2	6.7	7.0	Very dirty
2	0.014	0.7	0.0	0.5	4.7	Moderately polluted
3	0.076	3.8	0.1	2.5	6.5	Dirty- very dirty
4	0.059	3.0	0.1	2.0	6.2	Dirty
			by nitrates content			
1	1.800	0.1	0.0	–	–	Slightly polluted
2	3.200	0.1	0.1	–	–	Polluted
3	6.200	0.1	0.1	–	–	Dirty
4	5.700	0.2	0.1	–	–	Very dirty
			by nitrate nitrogen content			
1	0.630	0.1	0.1	0.1	4.1	Slightly polluted
2	0.310	0.0	0.0	0.0	1.2	Very clean
3	1.440	0.1	0.1	0.3	6.4	Dirty
4	1.390	0.2	0.1	0.3	6.2	Very dirty
			by phosphate content			
1	1.100	7.1	0.3	5.4	7.0	Very dirty
2	0.710	4.0	0.2	3.0	7.0	Very dirty
3	0.820	5.8	0.2	4.4	7.0	Very dirty
4	0.900	6.7	0.3	5.0	7.0	Very dirty

an increase in turbidity, salinity, and bacterial concentration. One of the components of the eutrophication process is the proliferation of cyanobacteria, also known as blue and green algae. Several of these algae produce toxins that fall under the category of phosphorus and sulfur-containing organic compounds, which can be neuro-paralytic. The toxins produced by these algae can result in various health issues such as skin disorders and gastrointestinal ailments. In severe cases, paralysis may even occur when a substantial amount of algae enters the body.

Biochemical oxygen consumption. The $MPC_{household}$ of BOD5 is 3.0 mg/dm^3; for $MPC_{fishfarm}$ it is 2.0 mg/dm^3. According to European standards, the BOD5 indicator is not normalized in recreational reservoirs. BOD5 identification in the surface waters is used to assess the content of biochemically oxidized organic substances, the living conditions of hydrobionts, and as an integral indicator of water pollution.

Dissolved oxygen. The $MPC_{household}$ for the content of oxygen dissolved in water is >4.0 mgO_2/dm^3; for $MPC_{fishfarm}$ it is >6.0 mgO_2/dm^3. According to European standards, the content of oxygen dissolved in water in recreational reservoirs is not normalized. The content of oxygen dissolved in water reflects the intensity of the processes in the hydrobiochemical systems. The oxygen identification in the surface waters is included in the observation programs to assess the living conditions of hydrobionts, including fish, as well as indirect features of surface water quality assessment and wastewater treatment management. The content of dissolved oxygen is necessary for aerobic respiration and is an indicator of biological activity (i.e. photosynthesis) in the reservoir.

4.5. Managing a transformed river basin

The assessment of the transformation level in the Buniv River basin makes it necessary to improve the monitoring system within the river basin, as the main tool for assessing and predicting changes in the aquatic ecosystem and managing the processes of its anthropogenic transformation. Water quality monitoring can be effectively supported through the use of satellite technology [12, 13].

The basic model of monitoring the condition of the Buniv River and its objectives can be presented in the form of a diagram given in figure 6.

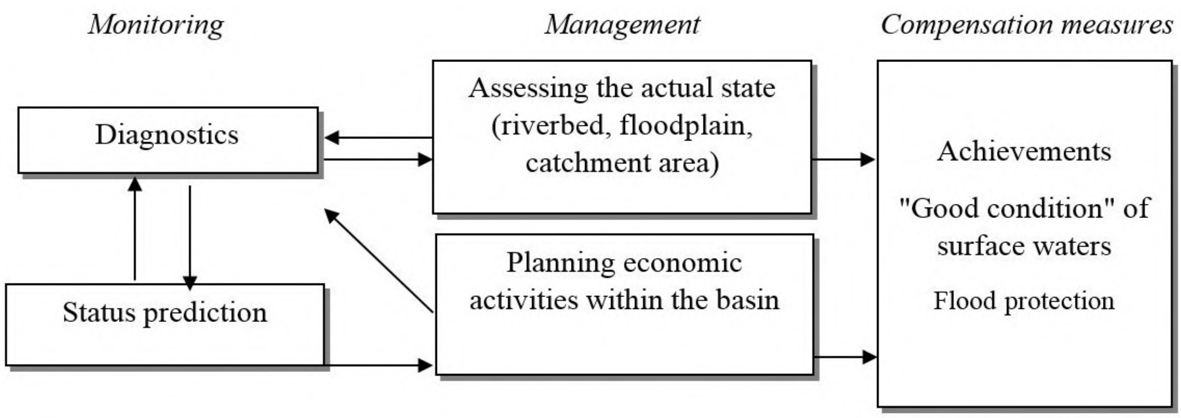


Figure 6. Flowchart for surface water quality monitoring and management.

Public environmental monitoring, if implemented, could be a valuable supplement to the existing system of monitoring water bodies. This will increase the availability of environmental information for all stakeholders, quickly obtain the necessary data in the event of an emergency accident, as well as current, regular monitoring of the impact of water users on the ecological state of the rivers. Local public organizations in the framework of public monitoring should perform the following functions: monitoring objects that are not included in state monitoring programs; implementing environmental control and notification of accidents and emergencies; developing environmental education and awareness; evaluating the environmental impact of projects for planned activities within river basins, etc.

For the effective management of border area basins, including the Lva River, it is necessary to create a Basin Council, which will include the representatives of Sarny District Administration, the Rivne Regional Office of Water Resources, the State Environmental Inspectorate in Rivne region, scientists, public activists and water users of the river basin. The main task of Basin Councils will be to develop, coordinate and approve the River Basin Management Plans. An important issue in the Council's activities is monitoring the implementation of the planned water protection measures within the river basin.

5. Conclusions

For the effective management of water resources in border areas, it is necessary to develop and implement water protection measures that are defined in the river basin management plans and develop and implement a joint program for public monitoring of the cross-border rivers.

The increase in the social and economic risks in the study area and the material losses associated with flooding the households in the floodplain of the Buniv River are caused by anthropogenic factors, namely, the development of the river floodplain, the violation of the requirements of the Water Code of Ukraine and ignoring the danger from natural flood and overflow phenomena.

It is possible to reduce the threat of territorial flooding and ensure the flood safety of the river cross-border territories of the Polissia zone by applying organizational and economic measures and implementing the following compensatory hydraulic measures:

- A periodic clearing of the riverbed section adjacent to the bridge from the deposits coming from the upper sections. This will help to increase the slope on the site, reduce the hydraulic resistance of the bottom turbulence and reduce the likelihood of spillway operation in semi-pressure and pressure modes;
- Reducing the resistance of water flow at culverts and reservoirs, creating flood corridors.

Reservoirs require developing regulatory rules that provide for the level of water response depending on the current meteorological situation. Thus, if the amount of precipitation in three days reaches 20 mm, then it is already advisable to clear the river valley, prepare households for high water levels and work with both reservoirs in order to overcome flooding.

The most effective approach to prevent flooding of large areas of Rokytne is to prevent the inflow of significant water consumption within the city limits. To do this, one should: arrange structures above the village that will allow the transfer of runoff through a network of channels.

The surface water quality assessment shows that the overall ecological state of the surface waters of the studied aquatic ecosystem is assessed as unsatisfactory. The block of tropho-saprobiological indicators is dominant and determines the water quality. At the same time, its deviation from the environmental standards is primarily caused by the biogenic elements of the nitrogen group (ammonium, nitrite and nitrate nitrogen) and phosphates.

In the upper and middle part of the river basin, it is necessary to carry out organizational and economic measures to reduce the inflow of pollutants with diffuse runoff, as well as hydraulic works to clear the riverbed and the riverbank stabilization. Also, in the middle section of the river, it is necessary to clean the surface waters of the river from the excess regional content, nitrite nitrogen, phosphates; we propose equipping a bioplateau according to the type of surface flow and an aeration treatment corridor.

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References

[1] Afanasyev S O 2019 *Hydrobiological Journal* **55**(2) 3–17 ISSN 0018-8166 URL https://doi.org/10.1615/HydrobJ.v55.i2.10

[2] 2011 *Second assessment of transboundary rivers, lakes and groundwaters* (United Nations Publications) ISBN 978-92-1-117052-8 URL https://unece.org/second-assessment-transboundary-rivers-lakes-and-groundwaters

[3] 2019 Velyka voda v Rokytnomu: zatopleni budynky, znyshcheni polia, rozvalena doroha [Big water in Rokytne: Flooded buildings, destroyed fields and roads] URL https://rivnepost.rv.ua/news/velika-voda-v-rokitnomu-zatopleni-budinki

[4] Klymenko O M and Statnyk I I 2012 *Metodolohiia pokrashchennia ekolohichnoho stanu richok Zakhidnoho Polissia (na prykladi r. Horyn) [Methodology for improving the rivers' ecological state in Western Polissia (on the example of Horyn river)]* (Rivne: NUWEE) URL http://ep3.nuwm.edu.ua/1841/

[5] Aristarkhova E O, Fedoniuk T P, Romanchuk L D, Latushynskyi S V and Kot I V 2021 *Journal of Water and Land Development* (49) 104–110

[6] Gopchak I, Kalko A, Basiuk T, Pinchuk O, Gerasimov I, Yaromenko O and Shkirynets V 2020 *Journal of Water and Land Development* (46) 97–104 URL https://doi.org/10.24425/jwld.2020.134201

[7] Vystavna Y, Frkova Z, Celle-Jeanton H, Diadin D, Huneau F, Steinmann M, Crini N and Loup C 2018 *Science of The Total Environment* **637-638** 1358–1362 ISSN 0048-9697 URL https://doi.org/10.1016/j.scitotenv.2018.05.095

[8] Trach Y, Melnychuk V, Melnychuk G, Mazur L, Podlasek A, Vaverková M D and Koda E 2021 *Desalination and Water Treatment* **232** 346–356

[9] Malovanyy M, Boiaryn M, Muzychenko O and Tsos O 2022 *Journal of Water and Land Development* (55) 97–103 URL http://journals.pan.pl/Content/125495/PDF/2022-04-JWLD-12.pdf

[10] Volchak A, Meshyk A, Mazhayskiy Y, Rokochynskiy A and Jeznach J 2020 *E3S Web of Conferences* **212** 01015 URL https://doi.org/10.1051/e3sconf/202021201015

[11] Hryb Y, Klymenko M and Sondak V 1999 *Restorative hydroecology of disturbed river and lake systems (hydrochemistry, hydrobiology, hydrology, management)* vol 1 (Rivne: Volynski oberegy) ISBN 966-7518-16-7

[12] Ciężkowski W, Frąk M, Kardel I, Kościelny M and Chormański J 2023 *Scientific Review Engineering and Environmental Sciences (SREES)* **31**(4) 283–293 URL https://doi.org/10.22630/srees.4482

[13] Giuliani C, Veisz A C, Piccinno M and Recanatesi F 2019 *European Journal of Remote Sensing* **52**(sup4) 64–73 URL https://doi.org/10.1080/22797254.2019.1689796

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Transformation of the national financial system of Ukraine: comprehension and ways of integration to sustainability

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Transformation of the national financial system of Ukraine: comprehension and ways of integration to sustainability

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Abstract. The article analyzes modern scientific approaches to sustainable finance and features of the transition of national financial systems, markets, financial flows in the direction from unsustainable to innovative sustainable technologies. The latest practice of implementing investment and financial activities in accordance with the goals of sustainable development is systematized. In the context of building a system of sustainable finance in Ukraine, the parity of two vectors of its functioning should be taken into account: ensuring both the sustainability of the financial sector itself and the sustainable functioning of the economy as a whole. That is, the development of the national system of sustainable finance in Ukraine is based on the generally recognized world practice in the field of sustainable finance and the decisions of the United Nations Organization, which relate to the financial aspects of sustainable development. In the context of this transformational process, Ukraine joined the Paris Agreement and received the Second Nationally Determined Contribution, which is a concept of state development to achieve ecologically and economically expedient transformations in all sectors of the economy. Financing of the Second Nationally Determined Contribution by 2030 should include a combination of domestic budget allocations, the private sector (domestic and foreign), bilateral and multilateral financial mechanisms, and international assistance. The article focuses on the need to understand the concepts and tools for ensuring financial stability, to determine the differentiated characteristics of the main directions of the transformation of the financial system and typologies of its transition. The authors single out the basic characteristics of transitions to sustainability and innovation processes: rethinking the achievement of new economic, environmental and social goals; time limit; creation of new socially inclusive, fair, ecologically sustainable economic systems; rejuvenation of the economic system through constant innovation; ensuring support for the financial orientation of transitions to sustainable development, which require integration and coordination of financial flows.

1. The problem

Since the Rio 2012 Summit, the issue of financing the needs of sustainable development has come to the forefront of the activities of the global establishment, academics and the business community. It is becoming increasingly clear that only with the establishment of a financial system that is sustainable and at the same time capable of providing financing for sustainable development can the complex of problems related to sustainable development of the state be effectively addressed. Over the past 20 years, the concept of sustainable finance has emerged and gradually become more widespread under the auspices of the United Nations Environment Program's Finance Initiative. It has accumulated a new financial paradigm of taking into account social, environmental and governance factors (the so-called ESG criteria) of sustainable development in financial activities, as well as the principles of responsible financial behavior. To date, the world has gained considerable experience in organizing sustainable financial activities in various industries and areas. However, in Ukraine, very little attention has been paid to the concept of sustainable finance, as well as to the theoretical, methodological and practical aspects of organizing sustainable financial activities to achieve the goals of climate stability and sustainable development. Therefore, the tasks of substantiating the theory and methodology of applying sustainable finance practices in Ukraine and adapting existing concepts of financial sustainability to the conditions of our country are very relevant.

The purpose of the publication is to characterize the possibilities of organizing a sustainable financial system in Ukraine to achieve the goals of climate stability, financing sustainable development and ensuring sustainable management in the country based on the implementation of the best international recommendations and practices in the field of sustainable finance.

2. State of finance in sustainability transitions research

The transition of the globalized economy and the world financial system to sustainable development requires a fundamental transformation of national financial systems, markets, financial flows in the direction from unstable to innovative sustainable technologies, the latest practice of implementing investment and financial activities in accordance with the goals of sustainable development. This applies both to the energy transition, where new low-carbon technologies are more capital-intensive and environmentally friendly, and to other areas of the economy, for example, the transition to sustainable urbanization, circular economy, green energy, etc.

It is undeniable that the transition to sustainability also concerns the financial sphere, which provides society with the necessary resources, and the economy with mechanisms and tools for financing changes. It should be noted that the specifics of the functioning of the financial system and its role in the transformation to sustainability have been studied by foreign and domestic scientists. Such interest in the scientific community is explained by the fact that financial capital is an interchangeable resource that is instantly directed to new technologies through free capital markets according to neoclassical economic models. Another feature of financial capital is that it has a wide variety of forms and structures, is often distributed through financial intermediaries and other actors whose activities are based on existing institutions and infrastructure [1].

Also, the "green" essence of sustainable finance is reflected in the distribution of idle social capital between different economic sectors, such as renewable energy, green cities and buildings, climate crises, corporate governance and environmental protection.

Having analyzed scientific publications related to the actualization and conceptualization of the transition of finance and financial systems to sustainability, it is possible to single out the following main directions of their research.

The first concerns research on the connection between financial crises and the transition to the concept of sustainability, as well as the direct development of conceptual approaches to ensure the development of sustainable finance. In particular, Geels [2] analyzes the crisis of 2008-2009, where attention is focused on its potential for the transformation of global economic systems, the possibility of initiating such a transition, and the analysis of state policies for responding to crisis phenomena.

The research by Quatrini [3] is devoted to the impact of the global pandemic crisis of COVID-19 on the transition to a sustainable future and sustainable investments, it is proposed to use decision support tools (DST) for ensuring sustainable development that contribute to investment decisions – ranking, sustainability ratings, standards, strategies, etc. The author comes to the conclusion that in order to effectively make an investment decision, it is necessary to change the existing practice of assessing sustainability, using new technologies and tools (artificial intelligence for checking the forecasting results, the rating model Impact ÆSSURANCE).

As mentioned above, publications related to the development of the conceptual foundations of the development of sustainable finance, the identification of connections between sustainability and, for example, "green" finance, should be included in this group of developments. This problem is highlighted by Wang et al [4], in which the authors emphasize that in order to achieve the goals of sustainable development, all sectors of society need to invest approximately 5 to 7 trillion US dollars annually, and the Paris Agreement provides for long-term financing with cost-benefit calculations, and within a certain period time and significant global investments.

Urban and Wójcik [5] offers a conceptual approach to sustainable finance as a multi-level socio-technical system in which the financial sector functions in a socio-technical landscape. The landscape is seen as a superstructure that includes various social groups and institutions governed by intersubjective norms that result from the process of globalization and capitalization of markets. In turn, as the authors note, capitalism and globalization, which are the main components of the modern financial regime, have a negative impact on both the regime and the trajectory of niche innovations. All this slows down the transition of the financial system to the conditions of sustainability.

Second, a number of scholars consider the availability of financial capital as an investment, energy, climate and environmental issue: for example, how new climate technologies and sustainable finance enable green growth, and using a cross-supplemented ARDL model found that climate technologies, access financial institutions to green investments and the circulation of green bonds (financial market efficiency) significantly reduce carbon emissions [6].

Furthermore, Ronaldo and Suryanto [7] prove that green investment (the indicators of which are waste management, investment in green enterprises and processing, ecological production) is of vital importance for achieving the goals of sustainable development of rural areas from the point of view of ecological and economic sustainability due to the implementation of "green" technologies, which in turn will lead to the development of "green" micro-entrepreneurship and improve the population's vital indicators.

In the framework of this direction, sufficient attention of scientists is devoted to the problems of sustainable financing and the development of the state policy of the transition to "green" energy. Besides, in the article [8], the impact of green financing and renewable energy sources (solar energy, bioenergy, hydropower and wind energy) on the sustainable development of China was investigated. Zhou and Li indicate that there is a significant need for an effective public policy regarding the widespread use of renewable energy to reduce environmental degradation and improve public health at a high level of economic activity.

Li et al [9] updated and modeled the connections between "green" financing, volatility and geopolitical risks regarding investments in renewable energy sources. The results of the study showed that green finance (in the form of green bonds) and green regulations, such as environmental taxes, play a significant and positive role in encouraging investment in renewable energy sources. Nevertheless, oil price volatility and geopolitical risk have a negative impact on the structure of investments in clean energy sources.

Thirdly, individual institutional components of the financial system are investigated, the prospects for their changes and the expansion of the range of financial instruments ensuring the transition of the financial market to sustainability are determined.

Since 2009, when the World Bank issued the first green-labeled bond for a group of Swedish pension funds, the market for fixed investment products has significantly evolved, expanded and diversified through the introduction of new structured finance instruments. In addition to green bonds, the market now offers blue bonds, social bonds, sustainable development bonds, disaster bonds.

Today, individual assets of direct investment funds, investment funds, exchange funds and those created on the basis of public-private partnerships, mixed financing instruments (multi-level investments) and risk-sharing instruments (guarantees, weather insurance, first loss capital), other instruments raising public and/or private sector capital for specific purposes, often related to achieving sustainability or other environmental or social commitments [3].

The transformation of the financial system into a sustainable one requires taking into account the prerequisites of the concept of sustainability in the activities of financial institutions, including banks. In the study [10], a benchmark assessment of the sustainability practices of 37 largest banks by total assets, located in Europe, America, Asia, Africa and the Asia-Pacific region, was carried out. The author found that the percentage of banks that adapted their management structure and implemented measures that contribute to increasing the level of sustainable development culture increased by 25% compared to 2020 and reached 74%. Banks have implemented the following measures: sustainability training programs (84% of assessed banks), sustainability policies (81%) and board statements on sustainability commitments (84%). However, it should be noted that the degree of consideration of non-financial factors varies depending on financial institutions. Usually, such actions are carried out by large international banks, for example, Societe Generale, Hongkong and Shanghai Banking Corporation-HSBC, Credit Agricole, Triodos).

Fourthly, part of the publications is focused on the issues of the systemic nature of sustainable finance (systemic approach) and the transformation of the financial system to the conditions of sustainability. Thomas and Mantri [11] considered finance as a complex adaptive system of systems (CASOS), which complicates its design for sustainable development using traditional approaches. The work proves that the problem of sustainability is multi-scale / multi-model, which is inherently adaptive and requires that adaptive agents evolve together with the corresponding cohort system. The authors propose an axiomatic approach to the design of sustainable finance that takes into account the vision of sustainable development as meeting the needs of the present without compromising the ability of future generations to meet their own needs.

Naidoo [12] conducted a thorough study of a new approach to overcoming the polarity of the financial system by interpreting the characteristics of the process of its transition to sustainability from the point of view of meeting certain requirements. According to the Naidoo, there are five initial requirements – changes in the direction of development, temporal dynamics, the influence of coexisting systems, a conflicting social context and contextual experimentation. That is, the article offers initial parameters that inform about the reaction of financial systems to the requirements of the transition to sustainability and make it possible to evaluate it.

Thus, the financial system is able to provide radical and transformational changes to sustainability in the economy, large-scale investments in infrastructure, despite the challenges of the crisis. In addition, the challenge of the gradual transition to sustainable finance lies within an interconnected global financial system that is struggling to keep pace with the digital economy and ensure resilience to new risks. Therefore, the above-mentioned global contexts, challenges and the need to understand the possibility of gradual transformation of the national financial system to sustainability determine the relevance of this study.

3. The basic institutional foundation of the formation of the national system of sustainable finance in Ukraine

When considering the formation of the national system of sustainable finance in Ukraine, first of all, it is necessary to pay attention to the main positions of the national model of sustainable management, which is aimed at ensuring socio-ecological and economic growth due to the inclusion of natural, physical and human capital in economic circulation (input effects), ensuring the corresponding structural changes in the economy, primarily in the "green" direction, taking into account the climatic requirements of sustainability (efficiency effect); the need to make powerful investments in the reconstruction and modernization of infrastructure, including both its industrial, social and environmental components (stimulus effects) and stimulation of relevant innovative activity, primarily in the field of development of environmentally friendly and climate-neutral technologies (innovation effects).

It is obvious that according to the above positions, building a system of sustainable finance in Ukraine must first of all take into account the parity of two vectors of such a system, that is, ensuring both the sustainability of the financial sector itself and the sustainable functioning of the economy as a whole. Thus, by building responsible financial behavior and purposeful financing of sustainable development measures, taking into account environmental, social and economic priorities, it is necessary to ensure the implementation of such processes as:

- firstly: the inclusion of natural, production, financial, human and other resources in economic circulation with the help of specific financial instruments – "green" instruments of the stock market, loans, insurance policies, etc.;
- secondly: sustainable financing of the "green" transition with the aim of minimizing climate change and reducing the economic burden on the environment as a whole;
- thirdly: the formation of powerful investment resources for the stabilization of the economy and the implementation of the investment policy of sustainable development,
- fourth: creation of a system of financial support for innovations aimed at greening the economy, "green" technological structural changes, minimizing the impact on the climate, taking into account the most modern trends in the implementation of the financial policy of sustainable development of the UN and the leading countries of the world.

Taking into account the above, the development of the national system of sustainable finance in Ukraine should be based on the universally recognized practice in the field of sustainable finance and the decisions of the United Nations Organization, which relate to the financial aspects of sustainable development. Thus, at the 75th General Assembly of the United Nations (UN) in September 2020, it was emphasized that the last decade has become the hottest in the history of mankind, the concentration of greenhouse gases continues to grow, so humanity must urgently change course, there are less than ten left years, and therefore already in the next decade, that is, by 2030, it is necessary to ensure appropriate changes in the management of the economy and finances in order to minimize further negative impacts on the natural environment and to allocate appropriate financial resources for this [13].

Today, it is recognized that climate and environmental challenges require a change in the financial policy of governments and individual financial institutions in the direction of organizing sustainable financial activities and forming an effective system of sustainable finance at the level of countries and the world. Today, climate and environmental challenges are recognized by the European Central Bank (ECB) as two main risk factors. According to the estimates of the Bank for International Settlements (BIS), they are one of the sources of systemic financial risks and may become the cause of the next global financial crisis [14]. The UN Framework Convention on Climate Change (1992), the UN Agenda for Sustainable Development until 2030, and the 2015 Paris Agreement on Climate Change are the main documents that countries should be guided by to confront climate challenges and achieve a sustainable future.

The specified documents, in particular, state that one of the three ways to combat climate threats in the context of sustainable development is to ensure the consistency of financial flows with the direction of low-carbon and climate change-resistant development of various-scale territorial entities (regions, countries, global economy, etc.).

According to these documents, starting from January 1, 2021, each country chooses its goals for reducing and/or limiting greenhouse gas emissions. Such goals are characterized as Nationally Determined Contributions (NDCs). The main goal of the Paris Agreement includes the following three sub-goals:

sub-goal (a): keep the increase in global average temperature well below +2 °C above pre-industrial levels and focus efforts on limiting temperature increase to +1.5 °C above pre-industrial levels, as this will significantly reduce the risks and impacts of climate change;

sub-goal (b): increasing the ability to adapt to the negative impacts of climate change, supporting climate change mitigation, development with low greenhouse gas emissions in a way that does not threaten food production;

sub-goal (c): harmonization of financial flows with the path of development, with countermeasures against climate change and with low emissions of greenhouse gases [15] (figure 1).

The main differences between the Paris Agreement and the Kyoto Protocol are as follows:

- First: changing the nature of the emissions reduction target from an “obligation” to a “contribution”. If the Kyoto Protocol provided for a legally fixed amount of greenhouse gas emissions for countries, which was not to be exceeded, the Paris Agreement gives each country the right to determine its contribution to the reduction of greenhouse gas emissions, taking into account national circumstances.
- Second: inclusion of all countries of the world with approved plans to reduce greenhouse gas emissions in the form of nationally determined contributions. The Kyoto Protocol provided quantitative commitments to reduce greenhouse gas emissions only from developed countries (Annex B to the Kyoto Protocol). Instead, the Paris Agreement consolidates contributions from countries that are Parties to the Paris Agreement.
- Third: introducing a bottom-up approach instead of a top-down approach, enabling all participants, not only at national, but also at local/local or even corporate levels, to contribute regarding the reduction of greenhouse gas emissions.

The participation of each individual country in achieving the global goal is determined by it individually and is called “Nationally Determined Contribution” (NDC). The Agreement requires that such contribution be “ambitious” and established “with a view to achieving the objective of the Agreement”. The country reports on participation and it is reviewed every 5 years.

Thus, participation in the Paris Agreement is largely voluntary and thus requires the development of appropriate frameworks and formats for sustainable financial behavior based on voluntary responsibility. The country’s participation is registered in the secretariat of the Framework Convention. Each subsequent participation parameter should be more ambitious than the previous one. Countries can cooperate and combine their nationally defined parameters of participation.

During the UN Climate Conference in 2015, the participating countries set their own obligations – the “Intended Nationally Determined Contribution” (Intended Nationally Determined Contribution), which will serve as the initial nationally determined contribution, if the country does not provide another in accordance with the procedure established by the

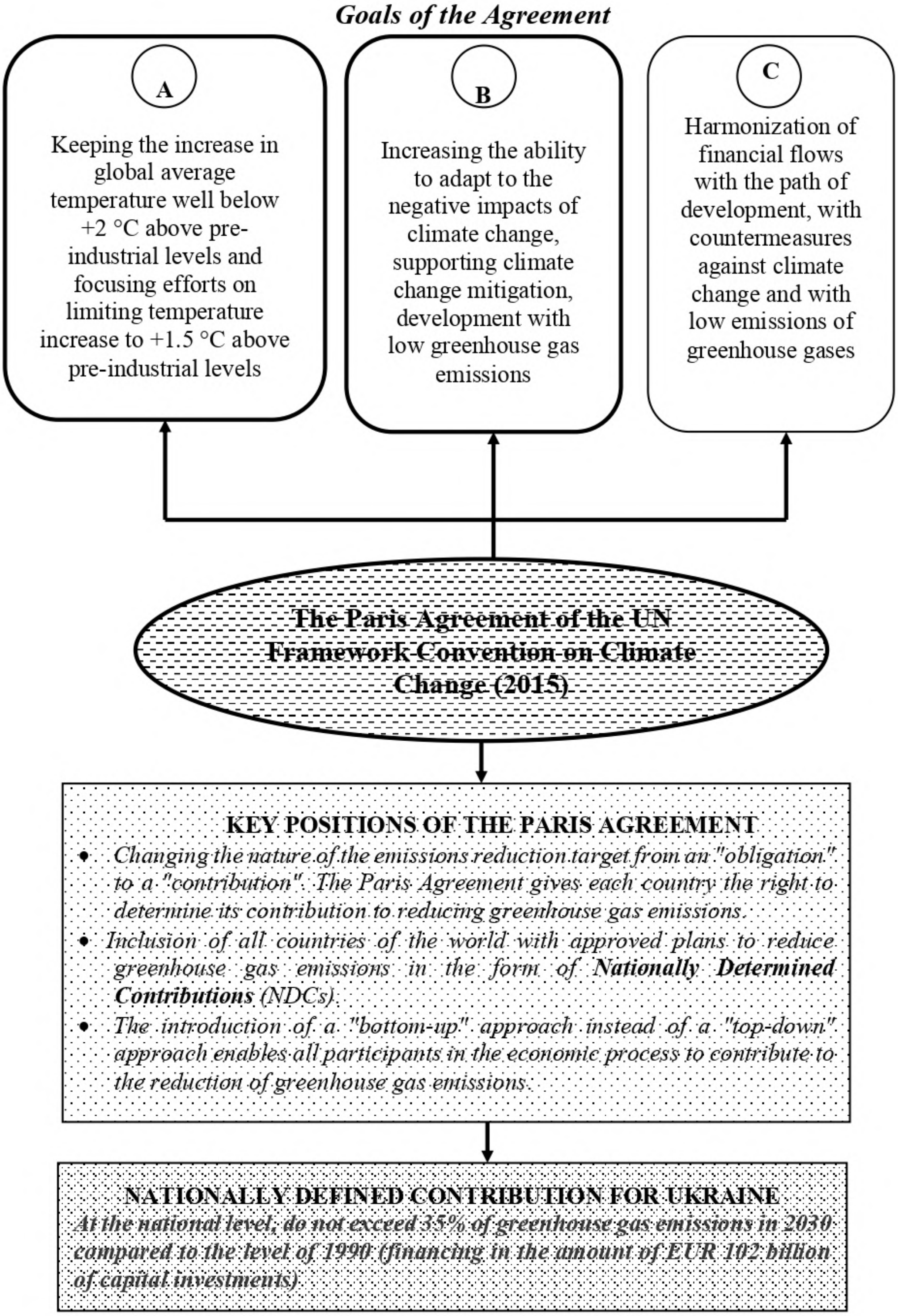

Figure 1. Formation of the nationally defined contribution of Ukraine to the Paris Agreement of the UN Framework Convention on Climate Change (based on [15, 16]).

Agreement. The level of each country's nationally determined contribution is determined by a voluntarily binding, but not mandatory, target.

At the end of July 2021, the government of Ukraine approved the updated national determined contribution of Ukraine to the Paris Agreement, according to which the current climate goal of Ukraine is to reduce greenhouse gas emissions to the level of 35% compared to 1990 by 2030 [17]. Among the main measures to achieve such an indicator in the next 10 years, it is necessary to implement and, accordingly, finance a number of economic tasks, which include: modernization of energy and industrial enterprises; development of renewable energy sources; energy efficiency measures in all sectors of the economy; thermal modernization of buildings; increasing the share of organic agriculture and resource-saving agricultural practices; electrification and renewal of transport; introduction of waste management hierarchy; increase in forest cover and reform of forest fund management [16].

It is noted that strategic goals for decarbonization and a consistent approach to their achievement are a logical continuation of Ukraine's European integration course.

4. Problems of financing the nationally determined contribution of Ukraine to the Paris Agreement

In order to achieve the declared goals of the transition to a low-carbon and resource-efficient economy and to ensure its sustainability, a clear state policy of sustainable financing is necessary, which involves not only a deep understanding of the content of environmental and social risks, but also the existence of an effective system for managing such risks. By financing relevant programs and projects, banks and other financial institutions play a key role in the decarbonization of the economy and the development of its resource efficiency.

In the context of the development of sustainable financing, Regulation 2020/852 of the European Union on the creation of foundations for the promotion of sustainable investment establishes six environmental goals of sustainable economic activity, namely mitigation of the consequences of climate change; adaptation to climate change; sustainable use and protection of water and marine resources; transition to a circular (closed loop) economy; pollution prevention and control; protection and restoration of biodiversity and ecosystems [18]. At the same time, the second (updated) nationally determined contribution of Ukraine to the Paris Agreement is the main document that will determine the goals set for achieving climate neutrality and the financial resources necessary for this. This document represents the concept of state development to achieve ecologically and economically expedient transformations in all sectors of the economy: energy, industry, transport, buildings, agriculture and forestry, waste management, etc.

Ukraine is a participant in key international agreements aimed at solving problems caused by environmental/climatic challenges. In accordance with the Paris Agreement of 2015, our state undertook to ensure that by 2030, the amount of greenhouse gas emissions produced by all sectors of the economy would not exceed 35% of the 1990 level. Achieving these goals requires strong financial support.

Thus, in March 2021, the Cabinet of Ministers of Ukraine approved the National Economic Strategy for the period until 2030 [19], according to which the country plans to achieve climate neutrality no later than 2060. According to experts, for the transition of Ukraine to a climate-neutral economy, it is necessary to attract about 102 billion euros of capital investments by 2030, that is, about 10 billion euros of annual financing [16]. The estimated investment plan is presented in table 1.

Financing of the Second (updated) Nationally Determined Contribution by 2030 should include a combination of domestic budget allocations, private sector (domestic and foreign), bilateral and multilateral financial mechanisms and development assistance. According to the experience of developed countries, the majority of resources should come from private investors, who are usually better at managing the risks associated with the construction and operation of

Table 1. Investments necessary to achieve the goal of the Second (updated) nationally determined contribution in 2021-2030 (project) [20].

Sector of the economic system	Capital investments, billion euros
In total	102
1+2. Energy + Industrial processes (without consumer spending)	93
Agriculture	2
Production of energy and heat	26
Industry	37
Buildings (excluding consumer spending)	16
Heating	16
Including thermal modernization of buildings	13
Extraction and transportation of energy resources	8
Transport (excluding consumer spending)	3
Private cars	3
3. Agriculture	2.3
4. Land use sector, changes in land use and forestry	3
5. Waste	2

facilities.

Thus, the role of the public sector will rather focus on providing the necessary regulatory tools, financial incentives and information that will facilitate the attraction of investment from the private sector. Both state and local budgets will play an important role in increasing capital investment in the various sectors of the economy represented in the Contribution. According to experts, financing from the private sector will provide approximately two-thirds of financing for the development of low-carbon infrastructure, and public sector resources will cover the rest through low-interest loans from state development banks or through special support programs [16].

Forecast calculations presented in the Project of analytical review of the updated nationally determined contribution of Ukraine to the Paris Agreement [16] lay the basis for the formation of a further algorithm of actions to ensure sustainable financing of the obligations of our state in accordance with the Paris Agreement.

Starting from August 27, 2022, the Ministry of Environment, together with the Ministry of Finance, the Ministry of Energy, the Ministry of Agrarian Policy, the Ministry of Infrastructure, the Ministry of Economy, the Ministry of Regions and the Government Office for the Coordination of European and Euro-Atlantic Integration have started the process of forming a road map of key transformations and measures to implement the updated nationally determined contribution to the Paris Agreement [21]. The operational plan of measures for the implementation of the updated nationally determined contribution to the Paris Agreement is being developed in order to strengthen internal coordination and monitoring of the implementation of climate goals, as well as to expand cooperation with international financial organizations and partners.

First, the plan should be broadly aggregated across all sectors represented in the updated Nationally Determined Contribution to the Paris Agreement and EBRD modeling results. Then, on the basis of these measures, the priority key transformations that the country must implement by 2030 will be formed, and the financial resources necessary for this will be identified. The document proposes, at the national level, not to exceed 35% of greenhouse gas emissions in 2030 compared to the level of 1990, or, in other words, to reduce greenhouse gas emissions by 65% in 2030 compared to 1990 [21]. The most important goal of developing such strategic documents for the development of climate finance in Ukraine is to ensure the effective use of public funds and the mobilization of private financial investments.

As an institutional basis for the formation of climate finance in Ukraine as a component of sustainable finance, national and territorial financial funds of the appropriate direction, budgetary institutions of the public financial sector and financial institutions of development can act. Ukraine can attract existing or create new state funds, for example a special state fund (Climate Fund, Green Transition Fund or Green Economy Fund).

In this way, it will be possible to finance climate projects both centrally and from various sources, as well as to facilitate their coordination and support transformations in selected sectors with the help of special programs. Examples of such institutions include the Modernization Fund operating at the EU level, and the National Fund for Environmental Protection and Water Resources Management operating in Poland. These funds are separate legal financial institutions that provide financing in accordance with accepted programs and criteria based on various support mechanisms – covering a portion of the loan, providing co-financing, grant programs, etc.

As financial institutions of the public sector, which are relevant to the climate component of sustainable finance, it is possible to consider, first of all, the state and local budgets, as well as the funds of various public organizations and associations. In particular, the State and local budgets should play an important stimulating role in increasing capital investments in various sectors of the economy. The main task is to create a favorable investment climate for the implementation of the “green” energy transition, to encourage business and private investors to invest in environmentally friendly technologies and infrastructure. One solution could be the extension of tax incentives to encourage green investments, for example, exemption from payment of sales VAT and excise tax on electric vehicles [22].

Development Financial Institutions (DFIs) will also play a major role in climate change financing and the formation of a national system of sustainable finance. Curently, there are many significant contributors to the financing of climate projects in Ukraine, including: Clean Technology Fund (CTF) of the World Bank; Global Environmental Fund (GEF), which operates in Ukraine through UNDP; UNEP and UNIDO; The Finland-Ukraine Trust Fund, established by NEFKO, and the Eastern European Partnership for Energy Efficiency and the Environment (E5P), established by the European Commission for the purposes of Ukraine. DFIs in the last decade have become an important source of sustainable investment in Ukraine, which ranks 4th in the world as a recipient of climate finance from such bilateral and multilateral sources.

In total, the EBRD and the EIB mobilized over 13 billion euros in loans and 2 billion euros in grants during 2014-2019, with the aim of helping Ukraine stabilize the economy and implement comprehensive economic reforms. The EIB mobilized €4.6 billion in loans to support infrastructure development and reforms in the transport, energy, agriculture, education and municipal sectors. EBRD investments in the amount of 4 billion euros were also attracted to promote the development and reform of the banking sector, agribusiness, transport and small business. In addition, the EU’s annual program of actions to support Ukraine is financed from the general budget of the EU.

Thus, in 2020, Ukraine attracted 165 million euros for several budget areas (agriculture and development of small farms; technical cooperation; civil society; climate actions) [16]. It is expected that the DFI will continue to play the role of a catalyst for attracting sustainable investment in Ukraine. According to the calculations of experts, if a third of the future financial aid to Ukraine from the EU in the period 2021-2030 is directed to projects to prevent climate change, about 10 billion euros can be attracted for Ukraine, which is equivalent to 1 billion euros per year, which, according to our according to estimates, it will cover at least 10% of the investments in our country estimated for climate goals.

The United Nations Development Program (UNDP) is also a powerful institution supporting the development of sustainable financing at the international level [23]. On January 24, 2022, in Kyiv, the National Bank of Ukraine and the United Nations Development Program (UNDP) in Ukraine signed a memorandum of cooperation (hereinafter referred to as the memorandum) in the field of development of sustainable financing standards and the application of environmental, social and management approaches (Environmental, Social and Governance – ESG) in the financial sector. According to this document, the parties will implement joint measures to ensure more sustainable, inclusive and "green" economic development with the aim of increasing the resilience of the financial system of Ukraine to environmental, social and managerial risks [24].

UNDP supported Ukraine's desire to create the necessary foundations for the development of sustainable financing in the country, taking into account the fact that the development of the "green" economy and "green" finance have become key areas of support for the authorities of Ukraine for UNDP. Thanks to the strategic partnership of UNDP and the National Bank of Ukraine, complex regulatory and institutional frameworks will be developed by 2025 to support sustainable financing in Ukraine in accordance with the previously proposed NBU Policy and Roadmap for the Development of Sustainable Financing in Ukraine. According to the statements of the leadership of the UNDP representative office in Ukraine, this organization is ready to further strengthen the potential of the National Bank to implement the Policy on the Development of Sustainable Financing for the period until 2025 and support the strengthening of the country's economy for the benefit of the Ukrainian people.

In turn, the National Bank of Ukraine undertook to actively work in the direction of promoting sustainable financing in accordance with the global concept of sustainable development and the European integration vector of Ukraine's foreign and domestic policy. According to the signed memorandum, experts of the National Bank will receive qualified advisory assistance from UNDP during the period of implementation of the Roadmap regarding the development of standards regarding the disclosure of information about environmental, social and management risks by financial non-banking institutions. First of all, it is important to hold online meetings dedicated to the review of international standards and practice on this topic. The parties will also cooperate with the aim of organizing corporate governance related to the introduction of ESG principles, developing sustainable financing standards and improving the management of environmental and social risks in banking and non-banking financial institutions.

Cooperation between UNDP and the National Bank will contribute to the implementation of the Agenda for the period until 2030 in Ukraine, strengthening the efficiency and involvement of the financial sector in the sustainable development of Ukraine with the help of non-regulatory mechanisms, as well as supporting an active dialogue between the public and private financial sectors regarding the financing of the Sustainable Development Goals with in order to better align policies, strategies and investment flows.

Despite the large-scale war in Ukraine, the country's government continues to implement planned measures to achieve the Sustainable Development Goals (SDGs). Thus, after a meeting with state institutions and development partners regarding progress in achieving the SDGs, the Secretariat of the Cabinet of Ministers of Ukraine announced its intention to conduct and submit a Voluntary National Review (hereinafter referred to as the Review) in 2023. The Review is a process by which countries assess and present national progress towards the 2030 Agenda for Sustainable Development and its 17 SDGs and 169 goals. All 191 UN Member States have agreed to achieve the SDGs by 2030, and countries are also expected to conduct at least two Reviews during the SDG implementation period.

The Voluntary National Survey in Ukraine for 2021 showed a decrease in the poverty rate from 58.3% in 2015 to 43.2% in 2018. However, these positive trends are quickly changing: early UNDP forecasts showed that up to 90% of Ukraine's population could face poverty and vulnerability to poverty if the war continues for another year [25].

Thus, the government of Ukraine and financial institutions are gradually implementing measures that will contribute to the further transition of the national financial system to sustainability, taking into account the country's losses from the destruction of energy, transport and urban infrastructure, the need to restore business in the post-war period.

5. Understanding the conceptualization of the transition to sustainable finance

For the development of state strategies and programs for the transition of the national financial system to sustainability, the necessary basis is a scientific conceptual understanding and justification of this process. In modern science investigating the transition to the sustainability of the world financial system, attention is focused on: differentiated characteristics of the main directions of transformation (taxonomy of sustainable development projects, disclosure of information on non-financial risks by non-financial institutions, standardization of requirements for instruments for mobilizing financial resources, disclosure and consideration of information on non-financial risks by financial institutions, formation (development) of the infrastructure of sustainable finance); determination of typologies of such transitions and their features [26]. Despite the heterogeneity of transient processes, certain main characteristics can be singled out, which provide the basis for conceptual understanding of this process.

In particular, transition processes are non-linear and destructive, aimed at achieving a new stable economic state of the system. In addition, multi-level and conflicting interactions are typical for transitional processes that lead to evolutionary (structural) shifts and the emergence of a new (innovative) type of systems and processes [27], when such systems demonstrate the possibility of variations and alternatives for choosing ways to achieve a new steady state.

The scientific basis of sustainable finance is the classification of the characteristics of transitional processes and practical consequences of the Paris Climate Agreement and the SDGs proposed in [12], which is illustrated in table 2. This interpretation is the result of the generalization of modern scientific developments at the initial stage of research, which will be further developed when it will be possible to implement conceptual and empirical conclusions obtained as a result of research on transitions to sustainable development.

According to the given conceptual approach, the characteristics of transitions to sustainability and innovation processes are distinguished, which are the result of technological revolutions and profound changes that will lead to the modernization and rejuvenation of the economic system, the impact of which goes beyond the boundaries of the created new industries or technologies. Thus, technological revolutions are a specific form of transition to sustainability, but at the same time it is necessary to take into account the following special characteristics of such a process. First, transitions to sustainability lead to a strategic rethinking of the achievement of new economic, environmental and social goals associated with existential threats and risks.

Second, such transitions are inherently time-bound processes that require acceleration to achieve certain results of transformative impact on the environment, society, and economy by 2030, while technological revolutions do not have specific time limits.

Third, sustainable financial systems generate impacts at the environmental and social levels, creating new socially inclusive, equitable, environmentally sustainable economic systems while simultaneously destabilizing old ecologically unstable and socially unequal ones. At the same time, technological revolutions may not reflect the social quality of innovations.

Fourth, sustainability transition processes aim at rejuvenating the entire economic system as a primary goal, paying more attention to system-level impacts that can be achieved through different types of innovation; while technological revolutions focus on innovation, and system-level impacts are positioned as an indirect consequence of their diffusion.

Fifth, the Paris Agreement and the SDGs support the financial orientation of transitions to sustainable development, which require integration and coherence of financial flows, while the

Table 2. Characteristics for informing the demand on the financial system [12].

Characteristics	Indicative demands placed on the financial system
Directional changes	The intermediaries, markets and infrastructure of the financial system consistently directs itself toward achieving a new sustainable economic system.
Temporal dynamics	The financial system responds across short, medium and longer-term timeframes to address the systemic needs of transition processes.
Co-existent system impact	The financial system generates environmental and social system-level impacts, by creating new socially inclusive, environmentally sustainable economic systems and simultaneously destabilising old environmentally unsustainable, socially unequal economic systems.
Contested social context	The financial system engages with a broad base of stakeholders in developing its response to support the transition process.
Contextual experimentation	The financial system experiments and applies adaptive approaches to address the contextual needs of sustainability transition processes.

financing of technological revolutions does not provide for such prerequisites.

Moreover, at the initial stage of development and unification is the terminological apparatus regarding such definitions as, for example, “green finance” (different interpretations of such institutions as the United Nations Economic and Social Commission for Asia and the Pacific, OECD, World Bank), definitions of individual financial segments and instruments, such as banking, bonds or institutional investments (China Banking Regulatory Commission, Global Sustainable Investment Alliance, International Development Finance Club), approaches to distinguish industries and technological sectors that primarily require sustainable investments [28].

6. Proposals for the Roadmap for the development of sustainable finance in Ukraine in 7 main areas of work

Taking into account European approaches to strategizing the development of the sustainable finance system and within the framework of the commitments undertaken when joining the global Sustainable Banking Network, in November 2021, the National Bank of Ukraine presented a comprehensive vision of building and future development of the sustainable financial sector in Ukraine – the NBU Policy on Sustainable Finance Development until 2025 as a separate document that is strategic for the formation of a sustainable finance system in our country. Overall, the NBU Policy on Sustainable Finance Development until 2025 is a comprehensive document that will help financial market participants to take into account the NBU’s holistic vision in their plans for the coming years and prepare in advance for the discussion and implementation of future regulatory changes.

The Policy on the Development of Sustainable Finance in Ukraine until 2025 proposes a Roadmap for the Development of Sustainable Finance in Ukraine until 2025, which aims to determine the actions of the National Bank of Ukraine to create a reliable, predictable and stable regulatory framework for the development of sustainable finance in the country, indicating specific time frames and taking into account the need to ensure consistency and adaptation of the banking system and non-bank financial institutions to changes [20].

The Roadmap for the Development of Sustainable Finance in Ukraine is detailed in the following 7 main areas of work. Our proposals to this Roadmap are summarized as follows.

With regard to the first area – improving corporate governance in banks and non-bank financial institutions (NBFIs) with regard to ESG factors, it is necessary to clearly define and detail the concept and structure of ESG factors in accordance with each of the sectors of financial activity, as well as to clearly define and implement the concepts of “sustainable finance”, “climate finance”, “green finance”, “low-carbon finance” in the legislation, taking into account national specifics.

In the second area – the development of ESG disclosure standards – the proposals relate to the formation of a complete, comprehensive and understandable list of financial services in the context of various types of activities in such a way as to exclude double or vague interpretation of terms and thus ensure, on the one hand, the protection of the financial sector from greenwashing, and on the other hand, the effective financing of green projects.

In the third area of developing requirements for banks and NFIs to manage environmental and social risks, it is necessary to adopt a new Law of Ukraine “On Environmental Insurance” and create a sovereign wealth fund in Ukraine, which will become a factor in stabilizing the banking system of Ukraine, including taking into account the impact of ESG-related risks.

In the fourth area – establishing criteria for evaluating and selecting projects for financing, taking into account their role in sustainable development, it is necessary to develop clear regulations for full and clear criteria for evaluating and selecting projects for financing with the participation of stakeholders from public administration, business, and society.

In the fifth area, which is the formation of a sustainable finance system in terms of ensuring that financial institutions disclose information on how sustainable their activities are, the proposals relate to the organization of a review and implementation of best international standards and practices in this area in the Corporate Governance Code of these institutions.

In the sixth area, the integration of climate aspects into the financial stability system, it is necessary to improve the national system of statistical indicators to assess the impact of climate aspects on financial stability and to supplement the Roadmap with a paragraph on attracting external international financial assistance for the use of prudential instruments for sustainable development.

In the seventh area, which concerns the organization of work and implementation of measures to raise the level of financial awareness of economic entities in the development of sustainable finance in Ukraine, it is necessary to organize a National Sustainable Finance Platform, as recommended by UNDP, in order to create an active space for communication and interaction between stakeholders to develop effective management solutions in the field of sustainable finance, provide advice on harmonizing the technical criteria of the EU and Ukrainian taxonomies and updating them. Ukraine also needs to develop specific practices for implementing sustainable finance policies in the national economic system.

In order to create a national sustainable financial system in Ukraine, it is necessary to give impetus to three powerful processes that are increasingly gaining momentum in the global economy.

The first of these is an inclusive process – the capitalization of natural resources and the inclusion of natural capital in financial valuations.

The second is the formation of a system of sustainable financial relations in various areas of financial activity – investment, banking, insurance, and stock markets.

The third process is the dissemination of innovative approaches of “good governance” and “new public management” to the organization of management of economic systems through platforms, which are focused on decentralization, consensus, participation and responsibility.

These are the areas in which stakeholders should focus their efforts in the process of implementing measures to organize a sustainable financing system in our country.

7. Conclusion

The development of the national system of sustainable finance in Ukraine should be based on universally recognized global practice in the field of sustainable finance and the decisions of the United Nations Organization, which relate to the financial aspects of sustainable development. The main documents that the government of Ukraine should be guided by in order to face climate challenges and achieve a sustainable future are the UN Framework Convention on Climate Change, the UN Agenda for Sustainable Development until 2030 and the Paris Agreement on Climate Change, according to the decisions of which the participation of each individual country in achievement of the global goal is determined by it individually and is called "nationally determined contribution".

In the context of the development of sustainable financing in Ukraine, the Regulation of the European Union 2020/852 on creating the foundations for promoting sustainable investment enshrines the six proposed UN environmental goals for sustainable economic activity, and the main document that defines the goals for achieving climate neutrality and the necessary financial resources is the Second (updated) the nationally defined contribution of Ukraine to the Paris Agreement, which represents the concept of state development to achieve ecologically and economically feasible transformations in all sectors of the economy: energy, industry, transport, construction, agriculture and forestry, waste management, etc.

Financing of the Second (updated) nationally determined contribution until 2030 should include a combination of domestic budget allocations, the private sector (domestic and foreign), bilateral and multilateral financial mechanisms and development assistance, while, according to the experience of developed countries, the majority of resources will come from private investors, and the role of the public sector will focus on providing the necessary regulatory tools, government guarantees, financial incentives and information that will facilitate investment from the private sector.

Starting from August 27, 2022, the Ministry of Environment, together with the Ministry of Finance, the Ministry of Energy, the Ministry of Agrarian Policy, the Ministry of Infrastructure, the Ministry of Economy, the Ministry of Regions and the Government Office for the Coordination of European and Euro-Atlantic Integration began the process of forming a road map of key transformations and measures for the implementation of the nationally determined contribution to the Paris Agreement, including the financial sector. in order to strengthen internal coordination and monitoring of the implementation of climate goals, as well as to expand cooperation with international financial organizations and partners, which requires a corresponding revision and modernization of the Roadmap for the development of sustainable financing in Ukraine, proposed by the National Bank of Ukraine, primarily in terms of the specification of measures for the development of legislation on environmental insurance, asset securitization mechanisms, application of prudential tools for sustainable development, etc.

The institutional basis for the formation of climate finance in Ukraine as a component of sustainable finance is at the stage of formation, and its main structural elements can be newly created national and territorial financial funds of the appropriate direction, budgetary institutions of the public financial sector and financial institutions of development, for example, a special state fund – the Climate Fund, the Green Transition Fund or the Green Economy Fund, etc., primarily for effective financing of the process of achieving Ukraine's Nationally Determined Contribution to the Paris Agreement.

Development finance institutions (DFIs) are significant contributors to the financing of climate projects in Ukraine, which ranks 4th in the world as a recipient of climate finance from such bilateral and multilateral sources, and climate change prevention projects in 2022-2030 for Ukraine may be at least about 10 billion euros of EU aid funds have been attracted, which is equivalent to 1 billion euros per year, and this, according to our estimates, will cover at least 10% of the funds calculated for climate goals.

Furthermore, in order to ensure the transition of Ukraine to sustainable finance, a necessary condition is the development of concepts and tools, the definition of differentiated characteristics of the main directions of transformation and typologies. Therefore, the research of connections between the characteristics of the processes of transition to sustainability and the requirements for the financial system is an urgent task of further scientific research.

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References

[1] Steffen B and Schmidt T S 2021 *Environmental Innovation and Societal Transitions* **41** 77–80 URL https://doi.org/10.1016/j.eist.2021.10.018
[2] Geels F W 2013 *Environmental Innovation and Societal Transitions* **6** 67–95 URL https://doi.org/10.1016/j.eist.2012.11.004
[3] Quatrini S 2021 *Ecosystem Services* **48** 101240 URL https://doi.org/10.1016/j.ecoser.2020.101240
[4] Wang K H, Zhao Y X, Jiang C F and Li Z Z 2022 *Economic Analysis and Policy* **75** 412–426 URL https://doi.org/10.1016/j.eap.2022.06.002
[5] Urban M A and Wójcik D 2019 *Sustainability* **11**(6) 1745 URL https://doi.org/10.3390/su11061745
[6] Li Q, Sharif A, Razzaq A and Yu Y 2022 *Technological Forecasting and Social Change* **185** 122095 URL https://doi.org/10.1016/j.techfore.2022.122095
[7] Ronaldo R and Suryanto T 2022 *Resources Policy* **78** 102839 URL https://doi.org/10.1016/j.resourpol.2022.102839
[8] Zhou M and Li X 2022 *Resources Policy* **78** 102816 URL https://doi.org/10.1016/j.resourpol.2022.102816
[9] Li Z, Kuo T H, Siao-Yun W and Vinh L T 2022 *Resources Policy* **76** 102563 URL https://doi.org/10.1016/j.resourpol.2022.102563
[10] Mazars 2021 Responsible banking practices: Benchmark study 2021 URL https://www.mazars.pl/content/download/1037302/54110016/version//file/Responsible%20banking%20practices%20-%20benchmark%20study%202021.pdf
[11] Thomas J and Mantri P 2022 *Patterns* **3**(9) 100585 URL https://doi.org/10.1016/j.patter.2022.100585
[12] Naidoo C P 2020 *Environmental Innovation and Societal Transitions* **36** 270–290 URL https://doi.org/10.1016/j.eist.2019.10.004
[13] World Meteorological Organization 2020 75th UN General Assembly spotlights Climate Action URL https://public.wmo.int/en/media/news/75th-un-general-assembly-spotlights-climate-action
[14] European Central Bank 2020 Guide on climate-related and environmental risks: Supervisory expectations relating to risk management and disclosure URL https://www.bankingsupervision.europa.eu/ecb/pub/pdf/ssm.202011finalguideonclimate-relatedandenvironmentalrisks~58213f6564.en.pdf
[15] United Nations 2015 Adoption of the Paris Agreement URL https://unfccc.int/resource/docs/2015/cop21/eng/l09r01.pdf
[16] Ministry of Environmental Protection and Natural Resources of Ukraine 2021 Analitychnyi ohliad onovlenoho natsionalno vyznachenoho vnesku Ukrainy do Paryzkoi uhody URL https://mepr.gov.ua/wp-content/uploads/2023/07/Analitychnyj-oglyad-NVV-lypen-2021.pdf
[17] Ministry of Environmental Protection and Natural Resources of Ukraine 2021 Uriad skhvalyv tsili klimatychnoi polityky Ukrainy do 2030 roku URL https://www.kmu.gov.ua/news/uryad-shvaliv-cili-klimatichnoyi-politiki-ukrayini-do-2030-roku
[18] European Parliament, Council of the European Union 2020 *Official Journal of the European Union* **L 198** 13–43 URL http://data.europa.eu/eli/reg/2020/852/oj
[19] Cabinet of Ministers of Ukraine 2021 Pro zatverdzhennia Natsionalnoi ekonomichnoi stratehii na period do 2030 roku URL https://zakon.rada.gov.ua/laws/show/179-2021-%D0%BF#Text
[20] Natsionalnyi Bank Ukrainy 2021 Polityka shchodo rozvytku staloho finansuvannia na period do 2025 roku URL https://bank.gov.ua/admin_uploads/article/Policy_rozvytok-stalogo-finansuvannja_2025.pdf?v=4

[21] Ministry of Environmental Protection and Natural Resources of Ukraine 2021 Uriad rozpochynaie protses formuvannia dorozhnoi karty zakhodiv u sferi zminy klimatu URL https://www.ukrinform.ua/rubric-polytics/3305542-urad-rozpocav-formuvanna-doroznoi-karti-zahodiv-u-sferi-zmini-klimatu.html
[22] Markevych K 2022 Normatyvni ta prykladni zasady formuvannia finansovoi systemy Ukrainy v umovakh staloho rozvytku URL https://rb.gy/ljbmf
[23] United Nations Development Programme 2023 UNDP in Ukraine: About Us URL https://www.undp.org/ukraine/about-us
[24] United Nations Development Programme 2022 UNDP, National Bank of Ukraine partner on development of sustainable finance in Ukraine URL https://www.undp.org/ukraine/press-releases/undp-national-bank-ukraine-partner-development-sustainable-finance-ukraine
[25] United Nations Development Programme 2022 Despite ongoing war, Ukraine plans to conduct Voluntary National Review in 2023 of its progress with the Sustainable Development Goals URL https://rb.gy/5dg50
[26] United Nations Development Programme 2022 Sustainable finance. EU Green Deal URL https://www.undp.org/sites/g/files/zskgke326/files/2022-08/5%20FINAL_Tree_Sustainable_finance_strategy_297x210mm_4%2B4_web_180822.pdf
[27] Serhieieva L, Kovtun O, Opalenko A and Ivanylova O 2020 *International Journal of Industrial Engineering & Production Research* **31**(4) 625–636 URL http://ijiepr.iust.ac.ir/article-1-1136-en.html
[28] UNEP Inquiry 2016 Definitions and Concepts: Background Note Inquiry Working Paper 16/13 Inquiry: Design of a Sustainable Financial System URL https://unepinquiry.org/wp-content/uploads/2016/09/1_Definitions_and_Concepts.pdf

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Accounting for social responsibility of business in the context of sustainable development

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Abstract. The paper focuses on the fundamental components of socially responsible business and their accounting in terms of dividing it into determinants that is justified by the emergence of corporate social reporting, the expansion of the boundaries of traditional accounting concerning the introduction of indicators related to social costs, environmental and atypical aspects. The aim of the research is to comprehensively analyze all components of the social accounting system, identify the peculiarities of socially responsible business in the context of sustainable development, and develop recommendations for the formation of methodological and organizational components of presenting relevant information in the reporting of enterprises. We have found that the modern system of social accounting reveals the facts of economic activities concerning the accounting of social costs, economic and environmental measures to make effective management decisions in terms of the impact of the enterprise activities on society, adapted to the requirements of the external and internal environment. An overview of scientific views on the essence of accounting for social reporting is considered using the methods of analysis, synthesis, comparison, grouping and generalization. The author's opinion of the social accounting system involving the following main determinants as accounting for social responsibility of business, formation of accounting information in terms of sustainable development, environmental consequences of activity, accounting for atypical social components, accounting for reputational capital, is considered. We have substantiated that further implementation of social accounting and preparation of annual reports based on the proposed elements, can help in the formation of corporate and social responsibility of the company, expanding the range of interested parties: partners, customers and investors, i.e., magnetizing in the form of reputational capital.

1. Introduction

In the last two decades, the issue of studying corporate social responsibility of business, reporting, social accounting, and auditing, both at the national and international levels, has become relevant in scientific circles. The basis for the changes is trends in the global economy leading to increased competition between countries for limited natural, socio-economic, and financial resources. The problem of accounting for the social responsibility of business in conditions of limitation of socio-economic and natural resources is designed to balance the economic, social, and ecological aspects of development. The concept of sustainable development is inextricably linked with the concept of social responsibility of business. The implementation of the principles of social responsibility in the practice of enterprise activity determines the need to account for such activity as the basis of the sustainable development of the enterprise. Therefore, there is a growing interest in finding new methods and, accordingly, the newest objects of accounting for socially responsible activities. The problems include the implementation of the ideas of social justice, corporate responsibility and sustainable development based on the theory of "interested persons". At the same time, the sphere of business is maximally integrated into the social and political environment, and the level of correlation of the state of individual systems and their elements as factors of development reaches maximum values. Under such conditions, there is a change in the purpose and functions of individual elements of the management process within the enterprise, including in the field of socially responsible activity and its accounting.

The issue of accounting for socially responsible activity in modern conditions and the purpose of certain types of it, is constantly raised in the socio-economic literature. Deegan defines social accounting as a direction in accounting that shows the degree of impact of company's activities on the environment [1], and Killian and O'Regan describes the accounting of socially responsible activities as a process that helps form the reporting of enterprises, which provides solutions to their social and environmental tasks [2]. Yang et al, substantiates that the goal of socially oriented accounting is the creation of an information system that allows comparing the results of economic activity with the social needs of society [3].

It should be noted that we share the position of Owen and Swift, who note that social accounting and reporting are an integral element of corporate reporting in a democratic society [4]. According to scientists, it is this type of reporting that allows businesses to develop a level of social and environmental responsibility that, in its turn, will allow the sustainable development of the entire society to be achieved. In the article, we tried to expand the boundaries of the research and modernize the vision of these authors concerning the main components of modern social accounting in conditions of sustainable development.

The aim of the research is to comprehensively analyze all components of the social accounting system, identify the peculiarities of socially responsible business in the context of sustainable development, and develop recommendations for the formation of methodological and organizational components of presenting relevant information in the reporting of enterprises.

A peculiar approach to justifying the need to create an account system of social accounting is presented by Cooper et al [5]. The purpose of the accounts, according to the authors, is to stimulate ideological and socially oriented activities, popularization of ecological ideas. From this point of view, social accounting is a tool for creating prerequisites for social justice in society. As a result of the research, the working hypothesis has been substantiated, which states that social accounting is an integral component of sustainable development of a modern enterprise. This was achieved through the application of a complex of specialized research methods, including mathematical and economic analysis. Such substantiation made it possible to formulate the basic components of reporting on social accounting and social costs of business, particularly in terms of disclosing information not only about internal corporate social responsibility but also external projects. Therefore, representatives of businesses should disclose in their reporting information about investments in sustainable development of society, such as educational projects, infrastructure, support for startups and innovations, territorial communities, eco-projects, and social partnerships. All the achievements outlined have formed the scientific novelty of the conducted research.

The issues of the characteristics of socially responsible business are considered in related studies [6–12] and recommendations in the field of social accounting [13, 14]. Baret and Helfrich [15] distinguish the concepts of tax, environmental, strategic, adaptive, actuarial, innovative, network, social accounting, and others. The analysis of the works of domestic and foreign scientists indicates insufficient theoretical development of the main provisions and components of socially significant activity and the lack of a unified point of view concerning the categorical apparatus and tasks of social accounting, social responsibility that determines the need for further research in this area. Therefore, our research is aimed at shifting certain emphasis of scientific interest to the accounting of socially significant processes and human value components.

The purpose of the article is to assess the costs of social direction and develop recommendations for the formation of methodological and organizational approaches to the preparation of corporate social reporting in modern business conditions.

To achieve the goal we should solve a complex of interrelated, consecutive tasks defining the objects of accounting for social responsibility of business, social accounting and their essence, elemental composition, and the components of modern social accounting, reviewing the indicators of the development of socially responsible business in the context of the progress of relevant costs.

2. Materials and methods

Recommendations and reporting standards being the main principles of social accounting, auditing and reporting are used in the work based on the study of international experience and analysis of modern practices [16–19]:

- The Social Reporting Standard of companies developed by the Institute of Social and Ethical Accountability AA1000 AS, based on the Triple Bottom-Line reporting method of John Elkington;
- SA 8000 "Corporate Social Responsibility" defining the requirements for social protection of employees, and aiming at respecting human rights and improving the working conditions of employees by companies;
- The international standard ISO 26000:2010 "Guidance on social responsibility" presenting recommendations on the principles of social responsibility, the main topics and issues related to social responsibility;
- GRI (The Global Reporting Initiative), an international reporting standard for voluntary application by organizations reporting on sustainable development. The Recommendations propose a list of specific indicators for reporting on social, environmental, and economic activities of the enterprise.

There are legal requirements for social accounting, auditing and reporting in some countries (e.g., Bilan Social in France). The Financial Times, together with the London Stock Exchange, publishes the FTSE4Good index, which assesses the performance of companies in the field of social responsibility and promotes investment in these companies.

According to different sources, accounting for elements of socially oriented components of business, social (non-financial) accounting has different interpretations: non-financial reports, reports on sustainable development, reports on corporate social responsibility, environmental accounting. Today, more than 400 companies prepare annual reports based on the results of social accounting and auditing, which cover issues of sustainable development and corporate social responsibility ("Triple bottom reports"), but the reports differ significantly in format, style, and assessment methodology (even in the same industry) [20].

Thus, non-financial (social) reports include reports of companies that contain not only economic, but also social and environmental indicators, which characterize the level of achieving the goals of economic sustainability, social well-being, and environmental stability of society by enterprises.

General scientific and specific research methods were used while studying the components of the accounting system of socially responsible activity, namely: comparison, analysis and synthesis when considering theoretical approaches to social accounting, analogy and abstraction in the process of systematizing research elements, specification and extrapolation when developing recommendations for approbation of theoretical assets in practical activities, establishment of specifics of implementation of corporate social responsibility programs against the background of assessment of the dynamics of indicative indicators of the development of socially responsible business.

To substantiate the working hypothesis of the article, which is formulated later on, the authors applied a complex of mathematical and economic analysis methods, which were systematized based on the approach of Vlastelica et al [21]. In the mentioned research, the authors identified the influence of individual elements of corporate social responsibility on the overall reputation of the enterprise using expert and respondent assessments. We adapted and supplemented this methodology for the needs of our own research. As a result, the authors formed a set of indicators for the effectiveness of business social expenditures, methods of their comparison, and ensured comparability, which allowed analyzing the impact of business social responsibility on achieving its sustainable development goals.

3. Research findings

Approaches to the definition of “socially responsible business” provide for achieving the overall goal of the enterprise’s activity in the form of maximum contribution to sustainable development. The social responsibility of business is a contract between a businessman and the society in which he operates. There is no single approach to the definition of a socially responsible business (“corporate social responsibility”), so we have formed different visions of the interpretation of its content (table 1).

Table 1. Definition of “social responsibility of business” [18, 22–24].

Source (author)	Definitions
ISO 26000:2010 ”Guidance on social responsibility” [18]	Social responsibility is the responsibility of an organization for the impact of its decisions and activities on society and the environment through transparent and ethical behavior that promotes sustainable development, taking into account the health and well-being of society; takes into account the expectations of stakeholders and complies with applicable law; is consistent with international standards of conduct and integrated into the activities of the entire organization
World business council for sustainable development [22]	Corporate social responsibility of business is a permanent commitment of business to promote sustainable economic development, in symbiosis with workers, their families, local communities and society as a whole to improve their quality of life
Green Book of the European Union [23]	Social responsibility of business – integration of social and environmental aspects into the daily commercial activities of enterprises and their interaction with stakeholders on a voluntary basis
G. Bowen [24]	Social responsibility of business is the implementation of such policies, making such decisions, or following such a line of behavior that would be desirable from the point of view of the goals and values of society

The active social position of the company is related to the social responsibility of business (SRB), which is usually understood as the responsible attitude of the company to its product or service, to consumers, employees, and partners, and constant interaction in dialogue with society, and participation in solving the most acute social problems.

We have generalized the interpretation of the definition "social responsibility of business", which we understand as the activities of a business entity aimed at satisfying the interests of all "stakeholders" in order to achieve the most favourable economic, environmental and social results, that is the main components of sustainable development. That's why, We consider that to ensure the sustainable development of society, the social responsibility of business is no less important than the development of economic infrastructure, political stability, or innovative development projects. Social responsibility and sustainable development are interrelated concepts that help businesses become more environmentally and socially responsible while ensuring their long-term profitability.

Therefore, it is important to implement the concept of socially responsible behavior in enterprises that strive for their own sustainable development. Consequently, such activity, as a new component of business, requires its own accounting to meet the information needs of stakeholders. That is why it is necessary to introduce the accounting of corporate social responsibility into domestic practice. Its purpose is to preserve values, determine the results of socially responsible activities, and satisfy all stakeholders.

SRB is widespread among European countries. In some countries (Denmark, France, Finland, Sweden), it is integrated into public policy, in others (Greece, Ireland, the Netherlands, Slovenia), socially responsible practices are exclusively the prerogative of companies.

Recently, the idea of corporate social responsibility (CSR is a free choice of the company regarding the obligations to improve the welfare of society by implementing appropriate approaches to doing business and allocating corporate resources [25]) has become widespread within the framework of international initiative of the Global Compact, the purpose of which is the implementation of general principles of social equality and environmental preservation, and the creation of conditions for business cooperation with trade unions and non-governmental organizations. Thus, private businesses, joining the agreement in cooperation with other social partners, will be able to contribute to the realization of the idea of forming a stable and open global economy.

In the European Union, the role of CSR is to support the sustainable development of companies that leads to the improvement of the situation on the labour market, as well as the quality of products and services provided by companies.

Therefore, it is important to implement the concept of socially responsible activities at enterprises. Accordingly, these activities require accounting. In Ukraine, insufficient attention is paid to socially responsible activities (SRB, CSR). We believe it is necessary to introduce social accounting into domestic practice for information support of socially responsible activities of domestic business entities.

The purpose of accounting for socially responsible activities is to preserve values, to determine the results of socially responsible activities, and to satisfy all stakeholders. The social function of entrepreneurship (usually in practice, the categories of "social responsibility of business", and "corporate social responsibility") are evaluated with the help of a social audit.

3.1. Substantiation of social accounting essence and its components

Modern forms of global accounting business communication in terms of sustainable development are aimed at establishing promising relations and stabilizing the economic environment. Social accounting is a process of forming systematic, relevant information that characterizes socially responsible activities of a business entity and directed at making social decisions within the concept of sustainable development of the enterprise.

Recently, companies have been trying to pay attention to the implementation of programs and projects of social orientation, such as support for environmental protection, health, healthy lifestyle, creation of favourable working conditions, prospects for career development of staff, charity, etc. It means that the formation of public accounting information – financial reports –

must take place from the standpoint of sustainable development.

The combination of three main components of society's life: economic, social, and environmental, is embodied in the concept of sustainable development. This is a concept that describes the relationship between the social and environmental impacts of a company's economic activities on certain interest groups and on society, and is an important element of corporate social responsibility. It is this approach that will serve as a tool to ensure balance in the presentation of accounting information on social responsibility of business, certain social aspects, environmental factors of development and prospects of the enterprise.

Thus, social accounting covers: 1) accounting of corporate social responsibility; 2) accounting of sustainable development indicators; 3) environmental consequences of economic activities (accounting of social costs, the main part of which is related to the environment); 4) accounting of atypical social components (some accounting elements); 5) reputation capital (figure 1).

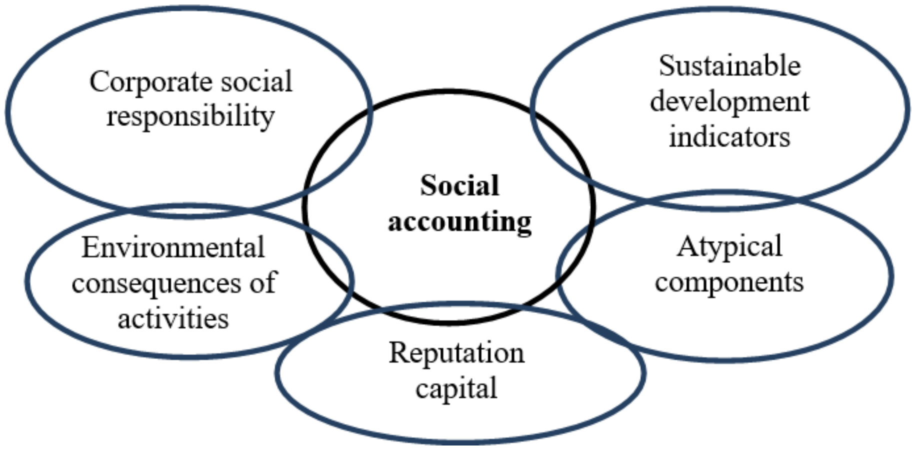

Figure 1. Components of the social accounting system.

According to its functional purpose, the social accounting system should be considered in the context of accounting subsystems (determinants) that characterize the state and use of labour resources. In terms of this approach, social accounting may be considered as a direction in accounting, which expands the boundaries of traditional accounting, reveals the facts of economic activity in accounting for social costs, economic and environmental measures in order to make effective management decisions on the impact of the enterprise on society, adapted to the requirements of the external and internal environment.

Thus, modern social accounting should combine the elements of accounting for social responsibility of business, environmental impacts of activities and relevant targeted measures, as well as the formation of accounting information in the context of sustainable development. In the practice of applying international non-financial reporting standards, such reports are called "Triple Bottom Line Reports". Each of these elements is aimed at highlighting the essence of various aspects of accounting, and accordingly has a different accounting essence.

3.2. The essence of corporate social responsibility accounting

Accounting for corporate social responsibility should reliably reflect the information on operations that affect the life of society and involve measures of green production, innovation of production technology and products; implementation of social programs and activities for both employees and society. Corporate social responsibility emerged as a response to the constant expectation of a more adequate and active role of business in society [21] and is directed not only external – to society and the business environment, but to its own staff. Research of practical activities by 469 American companies revealed a positive correlation between corporate responsibility of business and profitability of assets, sales growth, and proved that enterprises that consider the interests of all social groups grow on average four times more intensively than those that consider only the interests of shareholders [26].

Accounting information should reveal the costs of the enterprise to ensure the needs of its own employees, their motivation and improvement of external environment: the impact of business on the environment, health and education of the population, the state of renewable and non-renewable resources. It is also important to show the effectiveness of such expenditures, i.e., the ratio of their amount to the expected positive consequences in potential monetary terms, if they can be determined. It is the information as part of the company's annual reporting that will allow to present the business as a conscious, mature, and promising enterprise. To accept responsibility for the impact on society means, above all, that the company should report on its actions and keep records of them. Therefore, a conceptual approach that describes the relationship between social and environmental impacts on the company's economic activities and on certain interest groups is an important element of social responsibility.

Thus, the essence of corporate social responsibility accounting can be presented as a process of collecting, processing, summarizing and presenting accounting information on the costs of socially responsible activities and their potential or actual effectiveness.

3.3. Specific features of accounting for sustainable development

The concept of sustainable development is based on the thesis that the company's responsibility extends to all stakeholders. It is the stakeholder theory that is the basis of modern social accounting that significantly expands the scope of traditional accounting by introducing non-financial indicators that create new opportunities for the implementation of management control tools – Balanced Scorecard, Accountability Scorecard, Performance Pyramid, and other models.

Within this concept, a stakeholder is anyone who is directly or indirectly affected by the company's activities. This concept provides for the optimal use of limited resources and the use of environmentally friendly natural energy and material-saving technologies, including the extraction and processing of raw materials, the creation of environmentally acceptable products, minimization, recycling, and disposal of waste. From an environmental point of view, sustainable development should ensure the integrity of biological and physical natural systems.

Accounting for sustainable development is the most comprehensive element of accounting systems, but at the same time, in our opinion, it becomes a subsystem of social accounting. Sustainable development combines such aspects as environmental, social environment, microclimate of the enterprise, transformation of the company's goals, change of management priorities, etc. Accordingly, the management services of the enterprise should set themselves the task of analyzing the efficiency of current and future costs of the enterprise, assessing the impact of social and environmental measures. It is this approach of accounting for sustainable development that provides for the expansion of the subject of accounting from the presentation of exclusively retrospective information on economic activity (as provided by financial accounting) by including elements of analysis and risk management in accounting processes.

Thus, the essence of accounting for sustainable development may be presented as a process of processing and presenting accounting information in the part of implementation and evaluation of the effectiveness of current and future costs of the enterprise, the impact of social and environmental measures on the strategic goals of the enterprise.

3.4. Accounting for environmental consequences of economic activity

In the present conditions of technology development and the state of the planet, environmental accounting is distinguished as an independent subsystem. Within the scope of corporate social responsibility accounting, the level of disclosure of information on the environmental friendliness of business is insufficient. The enterprise, which claims to form a positive image in the society and cooperation with prospective partners, discloses information on the current state of environmental measures, their positive effects, environmental fees and means of overcoming the consequences of previous year activities in its annual report. Accordingly, the system of accounting data formation goes beyond the calculation and systematization of internal information. Instead, there is an active mutual integration of accounting data and methods of economic analysis, mathematical modeling, and forecasting.

On the other hand, the issue of environmental protection is a vital part of modern entrepreneurship. The phenomenon of Greta Thunberg is primarily due to the relevance and importance of the issues she raised [27]. At the same time, all skeptics are trying to calculate, i.e., to consider, positive and negative economic consequences of each of her steps. However, in our opinion, the main emphasis should still be on considering the environmental friendliness of your own business, not environmental organizations. Therefore, environmental accounting at the present stage is no longer a curiosity, but a necessary element of an effective accounting and analytical system. In the most general terms, social accounting provides information on personnel, products, and services, and focuses on the prevention or reduction of environmental pollution.

Thus, the essence of environmental accounting may be presented as the process of collecting, processing, summarizing, and presenting accounting information on the costs of retrospective and prospective environmental protection measures and their potential or actual effectiveness.

3.5. Atypical components of social accounting

Social accounting studies, controls and generalizes the processes related to the reproduction of material and social relations at the enterprise, in society. However, some aspects remain outside the analysis of socio-economic activity of the enterprise, as they are not subject to accounting data. We have called such components of social accounting atypical, i.e., those that do not comply with statistical expectations concerning social accounting or significantly deviate from it, but are those cases that characterize social stability and contribute to the effective operation of the enterprise and society as a whole, e.g., the structure of revenues by types of audit services, indicators of income inequality, charity, access to social investments, the presence of cases of social exclusion, inclusion of employees with disabilities, trade unions, gender equality, implementation of ethnic norms and values, etc.

Another positive example of the need to account atypical components can be the data of a survey of German companies on the positive correlation between investments in personnel development and the value of the company's shares. Accordingly, 87 percent of European companies' employees feel committed to socially responsible enterprises [28], and 33 percent of Europeans say that most of the economically active population would agree to work in a socially responsible company even if their salary is lower [29].

Accounting for atypical social components of the business entities' development is human-oriented and aimed at preserving the stability of social and cultural systems, in particular, at reducing the number of destructive conflicts between people, ensuring a healthy social and psychological climate in society, etc. An important aspect of this approach is the equitable distribution of goods and services.

3.6. Reputation capital as the result of social accounting and its formation in reporting

Non-financial accounting methods focus on the collection and registration of accounting data, their generalization and presentation in financial statements. As a result, an array of analytical information forms that serves as the basis for socio-economic analysis. While analyzing, the current efficiency of the incurred costs is calculated in terms of protecting the interests of own employees, conducting environmental measures, modernization of production technology and products, logistics systems, etc.

A feature of the accounting process of social accounting is the transformation of carriers of accounting nomenclatures. At the initial stage of social accounting, in addition to primary, purely accounting, documents, an important component of accounting nomenclatures are orders and economic justifications of the costs that will incur. At the stage of current accounting, there is a need to introduce own accounts for analytical accounting of non-production social and environmental costs. In addition, the company should provide a reasonable methodology for the distribution of such costs (as general production costs) depending on their materiality in terms of each individual type of product or service. At the stage of summarizing accounting, social accounting information is presented in annual reporting. The disclosure of such information in the numerical tables (forms) of the financial statements is incorrect. However, in the annual financial statements, it is possible to disclose all the necessary information in tabular forms, as well as in graphical and textual ones. It is at this stage of the accounting process that the goals and effectiveness of those measures that have become the objects of social accounting, are presented.

Presentation of such information in the annual reporting allows presenting socio-environmental risks and consequences of activities, justifying the necessity and effectiveness of the measures taken, etc. Reporting, formed by the triple bottom line method and containing social accounting information allows the company to form its own positive image in the business environment. Presentation of the company's social and environmental awareness in the annual reporting allows directing the users' opinion in the necessary direction for stakeholders. In our opinion, the positive image of the company can monetize in the form of reputational capital (goodwill) over time. That is, social accounting is not only a comprehensive method of processing accounting information, but also an effective management tool, especially value-oriented. Reputation capital is created by the enterprise from many details: product reliability and stability of payments, level of service offered to customers, investment attractiveness of business, employee satisfaction, environmental awareness, etc. Such capital can be seen as a value expression of the company's image in different markets and for different purposes. Accordingly, it can be valued also differently.

Thus, the process of quantitative assessment of reputation capital can be presented in the company's reporting in the context of social accounting: on the one hand, the result of realized social and environmental costs, and on the other hand, as their main goal, which is achieved in the form of economic efficiency.

3.7. Overview of success indicators of socially responsible business

In some studies on corporate social responsibility and social accounting as a fundamental component of sustainable development, the thesis that this is the prerogative of predominantly large businesses is directly or indirectly encountered. That is, large companies, as a maximum contribution to sustainable development, implement environmental activities (reduce environmental pollution, minimize and utilize waste, use natural resources rationally, implement programs for the health protection and strengthening of employees), educational projects, invest funds in the development of territorial communities and infrastructure of the region, create favorable conditions for personal development of personnel and improving their social security. In the conditions of the world COVID-19 pandemic, this thesis was partly refuted by reality, as even small companies invested funds in the safety of the environment and creating a barrier-free distance space for effective work in the context of sustainable development. However, the scale of costs of social responsibility and accounting mechanisms for their presentation for large consortia and holdings are integrated into the domestic business environment mainly from world experience.

A large-scale study in the American market confirmed the existence of a close direct link between the profitability of assets, sales, and their social activity, especially in terms of sustainable development. The performance of 300 corporations that have publicly stated the importance of ethics codes in their activities is two to three times higher than those companies, which have not done it. Enterprises that consider the interests of all community groups grow on average four times faster than those that consider only the interests of shareholders [26].

As experts in economics and business, Vlastelica et al [21] identified a successful set of indicators for evaluating the development and performance of social expenditures by businesses. In order to establish the characteristics of implementing corporate social responsibility programs by large businesses that contribute to sustainable economic development, we will supplement this set of indicators with measures of the number of employees in the enterprise, the total amount of expenditure on social projects, and the attractiveness of the business to employees, which we will use in our further calculations.

To determine the objects of research for evaluating the indicators of business development and its social responsibility in the context of sustainable development, we will use the data of Forbes analysts, who regularly compile rankings of the largest companies based on various criteria and parameters based on consolidated reporting [30], including Forbes' ranking of the best employers, which shows companies that best balance work and life for employees [31], and the DSNews ranking, which presents companies that carry out the best corporate social responsibility programs in Ukraine [32]. The comparison of the participants of these ratings shows that seven of them are present in all three ratings: Kyivstar, Sandora LLC (PepsiCoUkraine), MHP, Farmak, Metinvest, CarlsbergUkraine, AB InBevEfesUkraine.

The scale of business and peculiarities of their reporting unite all these enterprises, which also includes coverage of sustainability issues. These enterprises use international financial reporting standards, and present annual reports as part of not only financial reporting, but also reports on sustainable development and social responsibility reports [33–39]. The relevant business entities implement socially significant projects that do not bring them profit in the classical sense, but form the potential for the development of business environment and a positive business image, i.e., the prerequisites for the formation of reputation capital. In such reports, the main source of information on social responsibility today is the description of the relevant projects and the assessment of the total costs for their implementation (social responsibility costs).

The selected companies for analysis have access to the international market and are successful in terms of conducting business within the framework of sustainable development. The dataset for further analysis within these companies is provided in the Appendix to this article. The obtained time series based on comparing the growth rates of key business development indicators using the selected and previously adapted methodology [21] are grouped in figure 2.

Thus, as graphs show, the amount of social expenditures is not directly dependent on the profitability of the analyzed enterprises. Such projects are mostly permanent, and therefore, are implemented by businesses even in conditions of unprofitability. At the same time, the volume of social expenditures is growing at a rate similar to the growth of the business value itself, i.e., the scaling effect is working. Accordingly, we can say that the business social responsibility and the social accounting and reporting system formation should not be recognized as neither the cause nor the consequence of the enterprise development, but in modern realities, it is definitely an integral part of it.

The analyzed indicators may exhibit significant variability across different business sectors. However, their impact on the results of this study has been mitigated by using growth rate indicators, and for larger datasets, classic normalization methods with automated computational systems can be applied.

Socially responsible business forms its own positive business image, which is transformed into reputation capital. Due to this, the investment value of its securities increases, and therefore,

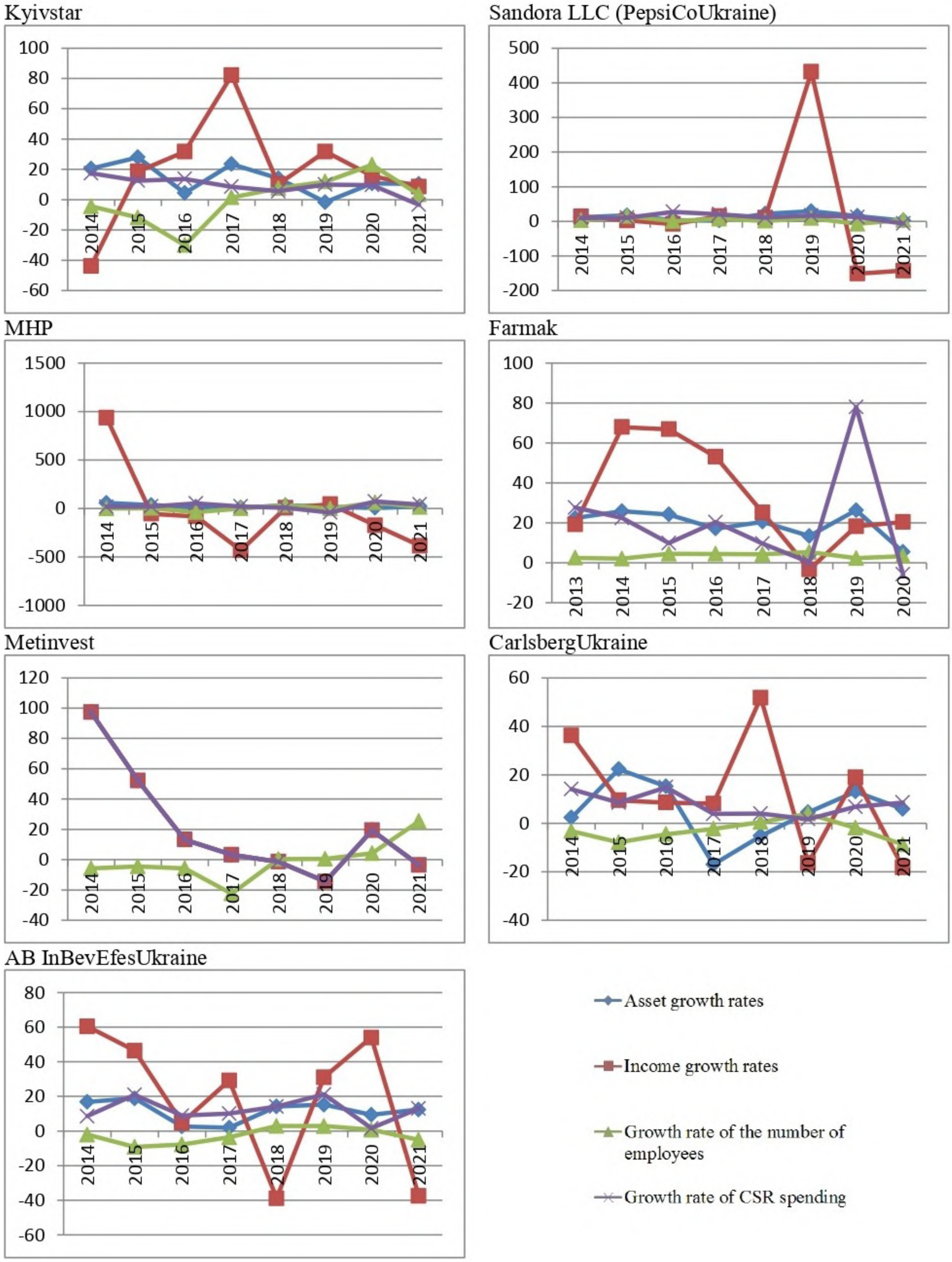

Figure 2. Dynamics of indicative indicators of business development and its social responsibility.

the reputation is monetized. A good example of the opposite effect can be the quotes of SpaceX, Tesla Inc and Twitter shares against the deterioration of their owner's image due to statements about the war in Ukraine, the increase in fees for the use of Starlink technologies in Ukraine and Poland, as well as a sharp deterioration in working conditions and social security of their own employees [40] (figure 3).

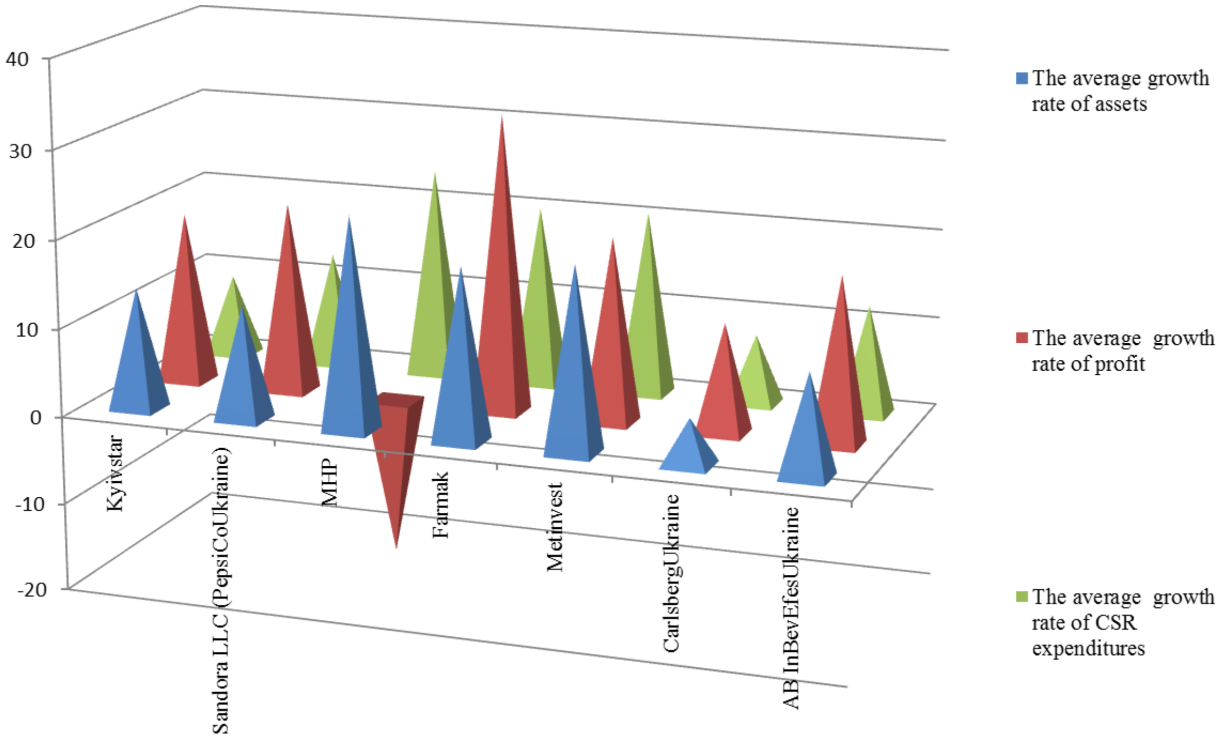

Figure 3. Comparison of average dynamics of key indicators of socially responsible business in the context of sustainable development.

Thus, as a result of the analysis, it has been proven that the actual amounts of corporate social responsibility expenditures from the perspective of sustainable development do not depend on profitability, but rather correspond to the scale of activities of the analyzed enterprises, since the average growth coefficient for a series of asset dynamics and the average growth coefficient for a series of social responsibility expenses dynamics for all analyzed enterprises are either identical or very close in value. In the future, the proposed working hypothesis can be empirically tested on a larger scale based on the methodology already presented.

So, reports on corporate social responsibility should be aimed at disclosing information about expenses made towards the relevant areas of expenditure. Such expenses should be perceived as investments in sustainable development of the external business environment, which over time convert into the company's own reputational capital and shape real growth in the value of the enterprise not just as a collection of assets, but as a value system. Accordingly, the organizational component should provide for the systematization of the information basis of such reporting: a list of social responsibility projects and the actual amount of expenses incurred for their implementation. The methodological component should include the formation of a unique approach to presenting this information by disclosing it according to socially significant directions: educational projects, infrastructure, support for startups and innovation, territorial communities, eco-projects, and social partnerships, among others. All analyzed enterprises already finance similar initiatives to some extent, but present information about them in the form of brief summary tables or concise presentations. In our opinion, disclosure and detailing of information on social expenses according to the specified directions (in the form of typical accounting tables with indicators of economic elements of the incurred expenses) will allow for creating preconditions for evaluating their effectiveness in the future. Moreover, disclosure of the actual components of incurred expenses will allow for evaluating the reality and scale of social responsibility projects of each economic entity. Thus, an educational project can be both a school trip to a production facility and the organization of a summer school with professional tutors. At the same time, the effectiveness and costs of these educational projects will be radically different, which should be illustrated by reports on social accounting.

4. Conclusion

We consider business social responsibility as the activities of a business entity aimed at satisfying the interests of all stakeholders in order to achieve the most positive economic, environmental and social results. Accounting of socially responsible activities may be considered as a direction in accounting, which expands the boundaries of traditional accounting, concerns many aspects and facts of economic activities: economic and environmental measures, implementation of social programs, building relationships with stakeholders, creating proper working conditions, implementation of ethnic norms and values in order to make effective management decisions on the impact of the enterprise on society, adapted to the requirements of the external and internal environment. Arguably, in order to ensure socially responsible activities of business entities, it is necessary to introduce social accounting into business practice. The study argues that in order to ensure the socially responsible activity of business entities, it is necessary to introduce social accounting into business practice. It has been proven that the modern system of social accounting contains the following main structural determinants: accounting of corporate social responsibility, accounting of environmental consequences of economic activity, accounting of sustainable development, atypical components of social accounting, reputation capital. These components are tangential, prolong each other, but have different essence. The social accounting system is implemented by combining methods of non-financial accounting, economic analysis and economic and mathematical modeling. In modern conditions, social accounting becomes an effective tool for enterprise management. Annual reports prepared using social accounting approaches present the company as a conscious, business-mature, and promising partner. Presentation of social accounting information in the annual reporting allows to present the effectiveness and prospects of the company's social and environmental measures and to promote the formation of reputation capital as monetization of the company's positive image in the growth of its total value and investment attractiveness in the market.

During the analysis of the criteria that describe the features of the implementation of social responsibility projects and their accounting process, we established that the amount of actual CSR expenditures does not directly depend on the profitable activity of the enterprise. However, it corresponds to its scale, because the average growth rates for a number of assets dynamics and social responsibility expenditures within the studied enterprises are either identical or quite close in value. The results of the analysis confirm the need for social accounting and the formation of reports on social expenses (which currently exist partially in the form of corporate social responsibility reporting), which in turn convert into economic benefits in the form of reputation capital. In other words, business investments in sustainable development of the external environment today will create conditions for their own sustainable development tomorrow and contribute to the growth of the value and worth of such businesses. As an expert in economics and business, I believe that this demonstrates the importance of considering social and environmental factors in business decision-making for long-term success.

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Appendix A.

Table A1: Calculation of growth rates of indicative business development indicators and its social responsibility.

Indicator	2013	2014	2015	2016	2017	2018	2019	2020	2021	Average growth rate for a series of dynamics
"Kyivstar"										
A	10944749	13192320	16879270	17618618	21751813	24809448	24393604	27013368	29812247	
P	3854635	2168375	2572679	3387067	6168938	6802455	8961220	10369859	11266926	
N	4149	3968	3500	2450	2486	2674	2992	3680	3804	
SRE	31500	37000	41650	47350	51400	54250	59650	65400	63200	
AG		20.535610	27.947699	4.3802131	23.459246	14.056920	-1.676152	10.739553	10.361089	13.7255224
P		-43.74629	18.645483	31.655251	82.132152	10.269467	31.735087	15.719277	8.6507155	19.3826421
N		-4.362497	-11.79436	-30	1.469388	7.5623492	11.892296	22.994652	3.3695652	0.14142486
SRE		17.460318	12.567568	13.685474	8.5533263	5.5447471	9.9539171	9.6395641	-3.363914	9.25512492
Sandora LLC (PepsiCo-Ukraine)										
A	2331534.5	2605066.4	3050429.1	3161066	3225578	3924682	5071435	5860243	5995029	
P	81632	93254	95654	88250	101250	111581	593229	-302480	128450	
N	2289	2354	2702	2715	2920	2963	3230	2990	3102	
SRE	7520	8256.3	9141.2	11641.6	14030	15632	18254	20514	19258	
AG		11.731844	17.096019	3.6269430	2.0408163	21.673759	29.219004	15.553941	2.3	12.9052907
P		14.237064	2.573616	-7.740398	14.730878	10.203457	431.65772	-150.9887	-142.4656	21.5259973
N		2.839668	14.783348	0.4811251	7.5506446	1.4726027	9.0111374	-7.430341	3.7458194	4.05675051
SRE		9.7912234	10.71788	27.35308	20.51608	11.41839	16.77329	12.38085	-6.122648	12.853517
MHP										
A	21343589	33411357	44860883	51796002	55789014	73946174	87413803	92820479	111943704	
P	1198255	-12417227	-5578761	-999966	3324384	3544102	5092533	-3760522	10720333	
N	30200	29923	30979	19100	19114	25750	25220	40960	46350	
SRE	72000	84000	101200	154000	186000	200000	117000	202000	284000	
AG		56.540482	34.268366	15.45917	7.7091124	32.546121	18.21275	6.185151	20.60238	23.9404
P		-1136.276	-55.07241	-82.07548	-432.4497	6.609285	43.69036	-173.8438	-385.0757	-276.8117
N		-0.91722	3.529057	-38.34533	0.073298	34.718	-2.05825	62.41079	13.1592	9.071191
SRE		16.66667	20.47619	52.1739	20.7792	7.52688	-41.5	72.6496	40.5940	23.67081
"Farmak"										
A	2235684	2736756	3444341	4278316	5011917	6040769	6851833	8655421	9124365	
P	202401	241411	405415	676383	1035217	1296353	1253843	1482977	1785326	
N	2150	2204	2250	2351	2456	2560	2698	2761	2854	
SRE	315230	402360	492650	541300	651320	714000	716292	1275000	1201320	
AG		22.41246	25.85488	24.2129	17.14696	20.5281	13.4265	26.3227	5.41792	19.415307
P		19.27362	67.93559	66.83719	53.05189	25.22524	-3.27919	18.2745	20.3879	33.46336
N		2.51163	2.08711	4.488889	4.46618	4.234528	5.390625	2.33506	3.36834	3.610297
SRE		27.64014	22.4401	9.875165	20.32514	9.62353	0.32101	78.00	-5.7788	20.3058
"Metinvest"										
A	135130	266584	405756	459689	474504	468098	400439	478010	461165	
P	3133	6181	9408	10659	11002	10854	9285	11084	10693	
N	100382	94581	90319	85096	66038	66241	66565	69383	86955	

Continued on next page

Table A1 – continued from previous page

Indicator	2013	2014	2015	2016	2017	2018	2019	2020	2021	Average growth rate for a series of dynamics
SRE	144	284	432	489	505	498	426	509	491	
AG		97.28012	52.2056	13.29211	3.2227	-1.34997	-14.4541	19.3716	-3.52401	20.75552
P		97.28012	52.2056	13.29211	3.2227	-1.34997	-14.4541	19.3716	-3.52401	20.75552
N		-5.77892	-4.50619	-5.78283	-22.3959	0.3074	0.48912	4.23346	25.326	-1.013471
SRE		97.28012	52.2056	13.29211	3.2227	-1.34997	-14.4541	19.3716	-3.52401	20.75552
CarlsbergUkraine										
A	3972005	4064795	4972260	5731056	4756605	4509135	4713533	5329646	5643378	
P	621148	845844	925697	1005025	1086424	1649287	1379265	1640449	1341539	
N	1751	1694	1561	1491	1457	1464	1522	1493	1362	
SRE	1625	1854	2012	2312	2402	2498	2541	2714	2946	
AG		2.3361	22.325	15.2606	-17.003	-5.20266	4.53298	13.0712	5.8866	5.15084
P		36.1743	9.44063	8.56954	8.0992	51.8088	-16.372	18.9365	-18.221	12.30446
N		-3.25528	-7.85124	-4.4843	-2.28035	0.48044	3.96179	-1.90539	-8.77428	-3.01359
SRE		14.0923	8.52211	14.9105	3.89273	3.99667	1.72138	6.80834	8.54827	7.811544
AB InBevEfesUkraine										
A	2079144.7	2428907	2888118	2965214	3022644	3450703	3975210	4348880	4888141	
P	-125410	-201164	-294561	-308651	-398835	-244105	-320101	-493000	-308741	
N	2369	2320	2108	1945	1875	1930	1985	2000	1898	
SRE	498	541	654	712	784	895	1084	1101	1245	
AG		16.82243	18.90606	2.669405	1.936799	14.16174	15.2	9.4	12.4	11.43705
P		60.40507	46.42829	4.78339	29.2188	-38.7955	31.1325	54.0139	-37.375	18.72642
N		-2.06838	-9.13793	-7.732448	-3.59897	2.9333	2.84974	0.75567	-5.1	-2.637374
SRE		8.634538	20.88724	8.8685	10.1124	14.15816	21.1173	1.56827	13.079	12.30318

Notation: Assets (UAH th.) – A; Profit (UAH th.) – P; Average number of employees (persons) – N; Social responsibility expenditures (UAH th.) – SRE; Asset growth rate (%) – AG; Profit growth rate (%) – P; Number of employees (%) – N; Social responsibility expenditures (%) – SRE.

References

[1] Deegan C 2017 *Critical Perspectives on Accounting* **43** 65–87 ISSN 1045-2354 25th Anniversary issue URL `https://doi.org/10.1016/j.cpa.2016.06.005`
[2] Killian S and O'Regan P 2016 *Accounting, Organizations and Society* **50** 1–12 ISSN 0361-3682 URL `https://doi.org/10.1016/j.aos.2016.02.004`
[3] Yang C, O'Leary S and Tregidga H 2021 *Qualitative Research in Accounting & Management* **18**(3) 313–331 URL `https://doi.org/10.1108/QRAM-05-2021-0093`
[4] Owen D and Swift T 2001 *Business Ethics, the Environment and Responsibility* **10**(1) 4–8 URL `https://doi.org/10.1111/1467-8608.00206`
[5] Cooper C, Taylor P, Smith N and Catchpowle L 2005 *Critical Perspectives on Accounting* **16**(7) 951–974 URL `https://doi.org/10.1016/j.cpa.2003.09.003`
[6] Murphy C B 2023 Financial Statements: List of Types and How to Read Them URL `https://www.investopedia.com/terms/f/financial-statements.asp`
[7] Planful 2020 What Is Financial Reporting and Why Is It Important to the Business? URL `https://hostanalytics.com/blog/what-is-financial-reporting/`
[8] 2018 financial report *Cambridge Business English Dictionary* (Cambridge University Press) URL `https://dictionary.cambridge.org/dictionary/english/financial-report`
[9] Noaman N, Ouda H and Christiaens J 2018 *E+M Ekonomie a Management* **XXI**(2) 186–207 URL `https://doi.org/10.15240/tul/001/2018-2-013`
[10] Perkhofer L M, Hofer P, Walchshofer C, Plank T and Jetter H C 2019 *Journal of Applied Accounting Research* **20**(4) 497–525 URL `https://doi.org/10.1108/JAAR-10-2017-0114`
[11] Al-Kassab J, Ouertani Z M, Schiuma G and Neely A 2014 *International Journal of Information Technology & Decision Making* **13**(02) 407–428 URL `https://doi.org/10.1142/S0219622014500497`
[12] Aversano N and Christiaens J 2014 *Financial Accountability & Management* **30**(2) 150–174 URL `https://doi.org/10.1111/faam.12032`

[13] Verkhovna Rada of Ukraine 2013 International Financial Reporting Standards (IFRS, IFRS forSMEs, including IAS and IFRIC, IFR) URL https://zakon.rada.gov.ua/laws/show/en/929_010?lang=uk#Text
[14] European Parliament and Council of the European Union 2014 *Official Journal of the European Union* **L 330** 1–9 URL https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32014L0095
[15] Baret P and Helfrich V 2019 *Journal of Management and Governance* **23**(2) 485–511 ISSN 1572-963X URL https://doi.org/10.1007/s10997-018-9430-z
[16] AccountAbility 2020 AA1000 Assurance Standard v 3 URL https://www.accountability.org/static/3ff15429033873cdc775212ca63572fb/aa1000as_v3_final.pdf
[17] Operatori Sanitari Associati 2020 Corporate Social Responsibility Management System (SA8000) - OSA coop URL https://www.osa.coop/en/corporate-social-responsibility-management-system-sa8000/
[18] ISO 2021 ISO 26000 – Social responsibility URL https://www.iso.org/iso-26000-social-responsibility.html
[19] Global Reporting Initiative 2023 GRI - Home URL https://www.globalreporting.org/
[20] Welc J 2022 Financial statement analysis *Evaluating Corporate Financial Performance: Tools and Applications* (Cham: Springer International Publishing) pp 131–212 ISBN 978-3-030-97582-1 URL https://doi.org/10.1007/978-3-030-97582-1_3
[21] Vlastelica T, Kostic S C, Okanovic M and Milosavljevic M 2018 *Journal of East European Management Studies* **23**(1) 10–29 URL https://doi.org/10.5771/0949-6181-2018-1-10
[22] World Business Council for Sustainable Development 2023 World Business Council For Sustainable Development (WBCSD) URL https://www.wbcsd.org/
[23] European Union 2006 Green Book of The European Union: The European Commission and CSR URL https://www.jussemper.org/Resources/Corporate%20Activity/greenbookeu.html
[24] Bowen H R 2013 *Social Responsibilities of the Businessman* (University of Iowa Press) ISBN 9781609381967 URL http://www.jstor.org/stable/j.ctt20q1w8f
[25] Kotler F and Lee N 2005 *Corporate Social Responsibility: Doing the Most Good for Your Company and Your Cause* (John Wiley & Sons, Inc.) URL https://archive.org/details/KotlerLeeCorporateSocialResponsibility
[26] Armstrong J S and Green K C 2013 *Journal of Business Research* **66**(10) 1922–1927 ISSN 0148-2963 strategic Thinking in Marketing Strategic Management in Latin America Corporate Social Responsibility and Irresponsibility Managing Global Innovation and Knowledge URL https://doi.org/10.1016/j.jbusres.2013.02.014
[27] 2019 Greta Thunberg condemns world leaders in emotional speech at UN URL https://www.theguardian.com/environment/2019/sep/23/greta-thunberg-speech-un-2019-address
[28] Lenssen G and Vorobey V 2005 Pan-European Approach *Corporate Social Responsibility Across Europe* ed Habisch A, Wegner M, Schmidpeter R and Jonker J (Berlin, Heidelberg: Springer Berlin Heidelberg) pp 357–375 ISBN 978-3-540-26960-1 URL https://doi.org/10.1007/3-540-26960-6_27
[29] Dey C 2007 *Accounting, Auditing & Accountability Journal* **20**(3) 423–445 URL https://doi.org/10.1108/09513570710748571
[30] Forbes 2021 100 largest private companies of Ukraine 2021 URL https://forbes.ua/ratings/100-naybilshikh-privatnikh-kompaniy-ukraini-2021-12102021-2580
[31] Forbes 2022 Top 50 employers 2022 URL https://forbes.ua/ratings/50-naykrashchikh-robotodavtsiv-2022-13012022-3179
[32] Stadzhi D 2021 Top 25 best CSR programs URL https://www.dsnews.ua/ukr/reitingi/top-25-luchshih-programm-kso-29062021-429340
[33] AB InBev Efes Ukraine 2022 Abinbev Efes - merezha peredovykh brovaren v Ukraini URL http://web.archive.org/web/20230225113133/https://abinbevefes.com.ua/
[34] Carlsberg Ukraine 2022 ESG Report Carlsberg Ukraine 2022 URL https://carlsbergukraine.com/media/57939/2022_report_ukr.pdf
[35] PepsiCo 2022 ESG Summary URL https://www.pepsico.com/our-impact/sustainability/esg-summary
[36] Kyivstar 2022 Investoram ta aktsioneram URL https://kyivstar.ua/about/investors-and-shareholders
[37] Metinvest 2022 Reports and results URL https://metinvestholding.com/en/investor/reportresults
[38] MHP 2022 ESG Reports URL http://web.archive.org/web/20230306052644/https://mhp.com.ua/uk/pro-kompaniiu/nefinansovi-zvity
[39] Farmak 2022 Financial statements and information about the Company URL https://farmak.ua/en/financial-statements-and-information-about-the-company-en/
[40] Durot M 2022 Elon Musk's Fortune Falls Below $200 Billion As Tesla Hits 52-Week Low URL https://www.forbes.com/sites/mattdurot/2022/11/08/elon-musks-fortune-falls-below-200-billion-as-tesla-hits-52-week-low

Ensuring the efficiency of forestry enterprises’ potential management as an element of sustainable development

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Ensuring the efficiency of forestry enterprises' potential management as an element of sustainable development

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Abstract. The paper is devoted to the problems of ensuring the efficiency of forestry enterprises' potential management. It was determined that forest plays a crucial role in ensuring people's living conditions, i.e., providing food, fuelwood, medicines, income, and employment, etc. Due to crisis tendencies in the forestry sector which were exacerbated by the full-scale war on the territory of Ukraine, the necessity of improvement of forestry enterprises' potential management is beyond doubt. The main problems of the forestry sector of Ukraine were outlined. It was determined that the ways of improving the forestry enterprises' potential management should be considered at national and individual enterprises levels. The peculiarities of the forestry sector reform and its planned outcomes were analyzed. It was proposed to supplement the measures of macroeconomic direction by enhancing the forest certification and implementing a participatory approach in management. Based on correlation and regression analysis, the main directions of measures for individual enterprises were defined. Such directions include reducing the duration of the operating cycle, increasing labour productivity, and increasing the rate of net income growth. The measures within each direction were proposed.

1. Introduction

The quantity and quality of resources available for the formation of living conditions determine humanity's existence. Forest resources are vital for human beings due to their role in society. Forests provide healthy food, fuelwood, medicines, income, and employment for people [1]. Forests are also a source of renewable materials in the case of rational resource use policy [2]. Forests are also important from the climate changes standpoint. According to World Economic Forum, deforestation is the factor that endangers climate on our planet, forming negative impact on natural environment and livelihoods, and almost 1.6 billion people depend on forest ecosystems for food, water, wood and employment [3]. During the last decades, due to inappropriate and irrational use of forest resources, deforestation and forest degradation have aggravated worldwide. This causes damage to both the natural environment and human living conditions, resulting in a wide range of issues related to environmental depletion. Thus, efficient policy in the sphere of forest management gains a crucial role in ensuring the well-being of society as a whole. We believe that such an efficient policy should be implemented at national and regional levels and at the level of individual enterprises, especially forestry enterprises.

It should be mentioned that the efficient use and reproduction of forest benefits achieving the sustainable development goals, which are the key guidelines for the development of humanity. In particular, the following goals are under the impact of forest conditions: SDG 2 "Zero hunger", SDG 3 "Good heath and well-being", SDG 6 "Clean water and sanitation", SDG 12 "Responsible consumption and production", SDG 13 "Climate action", SDG 15 "Life on land" [4]. Forest ecosystems are an essential prerequisite of society's sustainability model as they provide water conservation, wind and soil control, carbon sequestration, and biodiversity [5]. Thus, we can conclude that efficient forest management mechanisms are of particular importance in ensuring the sustainable development of individual countries and the world as a whole.

Efficient forest management is urgent for Ukraine, as the forest cover level has reduced significantly over the past century. The forest cover level in Ukraine is estimated at 15.9 %, while the optimal level is calculated as 20 % [6]. A lower-than-optimal level of forest cover determines the presence of problems related to the depletion of the natural environment, soil erosion, and decreased resource availability. It creates a threat to ensuring the sustainable development of the country. Thus, the development of effective mechanisms of forest use is an essential and urgent task, which is intensified due to the destructive consequences of hostilities on the territory of Ukraine. Considering the above, efficient forest management mechanisms should be implemented both at the national level and the level of individual enterprises. Therefore, we consider it necessary in this context to analyze the key factors of impact on the activities of forest-user enterprises and to propose directions for improving the management of the potential of forestry enterprises. This determines our study's relevance and identifies the key tasks to be implemented within the framework of the study.

2. Literature review

Forest resources are among the most crucial for people's existence, alongside water and soil resources. During the last decades, the processes of deforestation due to human activity, forest fires and increasing population have intensified significantly, causing such adverse effects as climate changes, extinction of plants and animal species, and total forest resources degradation. These reasons define the necessity for a balanced approach to forest management formation. Effective forest management is also one of the constituents of sustainable development, the key goals of which were defined by the UN General Assembly. The relevance, expedience and cruciality of the issues related to effective forest management system formation have shaped considerable scientific interest in the relevant sphere. This has been especially noticeable during the last decade, which is explained by the aggravation of many crises associated with rational forest use.

Forest ecosystems are crucial for sustainable development [5]. Zheng et al define that forests provide ecological, economic, and social benefits. The research is based on the idea of finding an appropriate management system in order to balance all of the aspects mentioned above. The authors use the Analytic Hierarchy Process method to define a model of indicators for forest management. The measures for effective forest management are also proposed in the paper [5].

Another research dedicated to the peculiarities of forest management was held by Knoke et al [7]. The authors emphasize the necessity of providing forest resilience under climate change conditions. The stability issue is quite essential for the forest case, as production time in forestry extends for long periods, which causes the vulnerability of forest ecosystems. The authors also define a relation between forest losses and economic losses, considering the role of forests in the country's economic development. Two silvicultural management systems are analyzed in the research, i.e. continuous cover forestry and clear fell forestry [7]. The research by Malindzakova et al [8] reflects forest management peculiarities and main directions. The system of indexes is used for the economic evaluation of forest management [8]. Mishenina and Dvorak [9] state that one of the ways to improve forest management from a national perspective is the implementation of a public-private partnership mechanism. According to the authors, public-private partnership contributes to sustainable development, decentralization, liberalization, and capitalization of natural resources. The characteristic features and advantages of the public-private partnership are also considered in the research [9].

Pietarinen et al [2] investigate the relationship between forestry and sustainable development in Finland. Scientists note that not all dimensions of sustainability have the same weight in the policy of forest use; the economic aspect dominates. Considering that Finland aims to be one of the key players in the bioeconomy based on forest use, the authors emphasize the need to strengthen ecological and social aspects in forming forest policy [2].

The participatory approach benefits the formation of an effective and efficient forest management system. It promotes decentralization in the corresponding sphere [1]. As Tessema and Nayak [1] state, participatory forest management contributes to sustainable management and forest ecosystems conservation, which is a vital issue for ensuring the stable development of society as a whole. The research deals with major aspects of the interaction of local communities with forest ecosystems in Ethiopia. Community forest enterprises are one of the manifestations of the participatory approach in forest management [1]. According to Piabuo et al [10], the role of community forest enterprises is similar to social enterprises, as they meet economic, social, and environmental challenges. The research is based on the Cameroon community forests enterprises and is aimed at their analysis, classification and activity study considering economic, social and governance dimensions [10].

An integrated approach reflecting a combination of participatory approach and forest certification is demonstrated by Degnet et al [11]. Using the example of forestry enterprises in Mozambique, the authors consider how the implementation of forest certification affects the well-being of communities living in the area adjacent to the forest [11].

Forest certification is another issue which has gained special scientific interest due to its relevance. Thus, Malek and Abdul Rahim [12] surveyed the publications dedicated to the forest certification aspect. The thematic analysis of forest certification literature dating from 2017 to 2021 was held. According to scientists, forest certification is important for achieving the sustainable development goals. The research provides a comprehensive analysis of the main trends in the forest certification literature of recent years and uses the results of the analysis to define gaps in the knowledge in the respective sphere [12]. Zubizarreta et al [13] analyze the certification processes in Spain regarding forests. The authors believe that the forest certification is a driver for forest management systems to be more environmentally and socially responsible. The paper defines the main motives for certification, based on a survey of 124 certified companies in Spain. Key mechanisms for certification promotion in Spain are also defined in the research [13].

Forest certification with a relationship to forest degradation in Sweden is reviewed in the research of Villabolos et al [14]. Two main certification schemes and their effects are considered in the article. The process and mechanisms of certification itself and maintaining the certificate are also defined in the paper. The authors investigate the impact of certification implementation on three indicators: environmentally important areas preserved during felling, the number of trees and high stumps left after felling, and the area set aside for conservation purposes [14].

Shvets et al [15] provide an analysis of the financial and economic activity at the example of forestry enterprises in the Zhytomyr region. The scientists have defined that the main challenges faced by the enterprises are those related to a decrease in demand, export issues, expenses increase, and inefficient human resources use. The authors' opinion on ways of solving relevant issues is provided [15]. Furdychko et al [16] directs its scientific efforts to solve the problems of balanced forestry land use. The work examines the dynamics of changes in the volume of forest resources based on a comparison of data for Ukraine and Poland, analyzes the impact of individual factors on the balanced use of forestry land based on the results of the production and economic activities of state forestry enterprises [16]. Tsehelnyk [17] provides a detailed analysis of the trends and conditions of the Ukrainian forestry industry and necessitates institutional changes in forest management mechanisms. Diadchenko and Saharnatska [18] consider forest enterprises management from a financial stability standpoint. The authors highlight the economic, social, and environmental components of the financial stability management model, as well as propose measures to increase the level of the corresponding indicator [18].

Summarizing the above, we should note that most scientific works are devoted to the determination of national-level levers of forest management, while the level of individual enterprises remains insufficiently covered, which determines the relevance of this study.

3. Objective of the research

The research aims to define ways to improve forestry enterprises' potential management based on internal factors which impact the respective enterprises functioning. The defined purpose involves solving the following tasks: to identify the role of the forest enterprises in the economy of Ukraine; to determine the consequences of the full-scale war on the territory of Ukraine; to consider ways of improvement of forestry enterprises' potential management at the national level; to detect key internal factors of impact on the functioning of the forestry enterprises; to propose measures for improvement of potential management at the level of individual enterprises.

4. Methodology

The methodological foundation of the research is a system method which allows to consider forest enterprises' potential management at both national level and level of individual enterprises. The set tasks involved the use of the following methods: monographic – to study and examine available publications on forest management; correlation and regression analysis – to identify key factors of impact on the formation of net profit of forestry enterprises; analysis and synthesis – to identify the key trends of forestry enterprises functioning; generalization – for formulating research conclusions; the deduction method – to propose and substantiate key measures for improvement of forestry enterprises potential management; graphical and tabular – to visualize the obtained research results.

5. Results of the research

Forestry is one of the essential segments in the economy of Ukraine. The sustainable development of forestry is based on the combination of ecological, economic and social functions of forests. Ukraine is a part of the world society that strives for the sustainable development of forestry. Forestry enterprises are obliged to conduct their activities based on sustainable development.

Balanced management of forestry combines a set of measures for the use, reproduction, formation, and protection of forests. The sustainable development of forestry is ensured under rational resource use, responsible consumption and reproduction. The economic activity of forestry enterprises to ensure sustainable development must be stable and efficient, that is, profitable. The enterprise's financial results depend on the sales volume of products and services.

The conditions for afforestation in Ukraine are heterogeneous, so forests are spread unevenly across the country's territory. The forest coverage of Ukraine is 15.9 %. Despite the relatively small area of forests, Ukraine ranks 9th in Europe in forest area and 7th in wood reserves.

Forestry in Ukraine, according to the "Classifier of types of economic activity", includes four groups: forestry and other activities in forestry (group 02.1), logging (02.2), collection of wild non-wood products (02.3) and provision of auxiliary services in forestry (02.4). Forest enterprises also provide services in several other essential industries: hunting, primary wood processing, food industry, etc.

According to the Land and Forest Codes, forests of Ukraine can be in state, communal, and private ownership. The vast majority of forests are in state ownership. About 1.3 million hectares (13 %) of forestry land plots in permanent use by municipal enterprises subordinated to local self-government bodies attribute to communal ownership.

Table 1. Main financial results of forestry enterprises of Ukraine

Indicator	Years			Deviation			
				2020 to 2019		2021 to 2020	
	2019	2020	2021	+/-	%	+/-	%
Funding from the general fund under budget programs, UAH billion	0.29	0.31	0.34	0.02	6.90	0.03	9.68
Net income from selling products (goods, works, services), UAH billion	15.20	14.46	22.80	-0.74	-4.87	8.34	57.68
Net profit, UAH billion	0.29	0.19	1.02	-0.10	-34.48	0.83	436.84
Profitability of activity, %	1.90	1.0	4.40	-0.90	-	3.4	-
Taxes paid, UAH billion	4.90	4.88	7.32	-0.02	-0.41	2.44	50.00

According to the information of the State Agency of Forest Resources of Ukraine [19–21], table 1 summarises the main financial results of forestry enterprises of Ukraine.

The generalised results of the activity of forestry enterprises of Ukraine [19–21] indicate the ambiguous financial performance of the industry. Over the past three years, there has been, in general, an increase in the net income from the sale of products (goods, works, and services), the net profit of enterprises, and the received amounts of budget financing.

However, financing from the general fund during 2019-2021 under budget programs was approximately 20 % of the need for budget financing. The tax burden has a significant impact on the financial condition of enterprises. On average, the percentage of paid taxes and duties on net income is 39 %. The most significant amount of taxes and fees to the budgets of all levels was paid by enterprises of the regional governments: Zhytomyr Oblast – UAH 873 million, Rivne Oblast – UAH 685 million, Chernihiv Oblast – UAH 553 million, Kyiv Oblast – UAH 534 million, Sumy Oblast – UAH 488 million, and Volyn Oblast – UAH 452 million.

According to Tsehelnyk [17], the main problems of forestry enterprises' potential management include the following:

- absence of a balanced strategy of development and management in the forestry sector;
- inaccurate distribution of management functions, which in some cases leads to duplication of functions or loss of their performance;
- financing disbalances;
- lack of effective mechanisms for stimulating the introduction of nature-preserving technologies;
- lack of a transparent mechanism for the timber sale, illegal felling and circulation of illegally harvested wood;
- the unsatisfactory state of ensuring the use of forests by local communities for recreational purposes.

The extremely important role of forests in terms of ecological, economic, and social sustainability of Ukraine determines the necessity to provide balanced resource-use mechanisms. It is necessary to balance the objectives of forest conservation, their ability to provide ecosystem services, the economic need for deforestation and the right of communities to profit from the exploitation of forests [16].

It should be noted that the activity of forestry enterprises is currently characterized by the presence of crisis tendencies, which are aggravated by the influence of a full-scale war.

The full-scale war in Ukraine affected the population, the economy, and the environment, including forests. Based on the materials of the EU4USociety project [22], the main problematic issues and prospects for developing forestry enterprises in Ukraine, particularly in war conditions, are summarised.

The main problem areas in war conditions:

1. *The difficulty of demining de-occupied territories.* Lands where active hostilities were fought, strewn with ammunition. Russia's active military operations complicate the speed of demining. Analysts emphasize that the cities and infrastructure will be demined first – it will take about ten years for the forests to be.
   According to WWF-Ukraine and the Regional Eastern Fire Monitoring Center [23], more than fifty different types of explosive munitions can be found in the forests of Ukraine that have fallen into the zone of military operations. Conventionally, the territory of the combat zone can be divided into the following types:
   (a) territories where active ground combat operations were conducted;
   (b) territories subjected to air bombardment and shelling from long-range ground units;
   (c) territories of deployment of military units;
   (d) territories that were mined to provide resistance to enemy troops.
   There is particularly little information on forest demining as of today, as surveys and demining were carried out locally, in small areas, primarily forest roads.
   According to the Institute for the Study of War [23], the areas of Polissia forests that were in the zone of military operations are as follows: Zhytomyr Oblast (127,789.8 ha), Kyiv Oblast (165,307.7 ha), Chornobyl Exclusion Zone (148,711.1 ha) Chernihiv Oblast (423499.0 ha), Sumy Oblast (287861.9 ha).
   A total of 114 state forestry enterprises, 20 agricultural enterprises, 14 municipal enterprises and 12 other forest users and owners were affected by military operations among enterprises and organisations whose activities are connected with forest. The most significant number of forests that have fallen into the zone of military operations is in the Chernihiv Oblast.
2. *Firefighting policy.* According to specialists, pristine pine forests are the most dangerous in the ignition. The map of hostilities shows that such forests are in the east of Ukraine, Polissia. Fires not only cause a loss of forest cover but also are a potential danger to the lives of residents. A possible scenario for territories with active hostilities is conservation with an analogue to the exclusion zone.
   WWF-Ukraine and the Regional East European Fire Monitoring Center [23] summarised that since the beginning of the war in Ukraine, fires have covered a total area of 2.4 million hectares, of which 1.5 million hectares (64 %) are in the territories with military operations and occupied territories: forests – 320 thousand hectares (13.1 %), agricultural land – 1340 thousand hectares (55.1 %), built-up areas – 129 thousand hectares (5.3 %), other natural landscapes – 645 thousand hectares (26.5 %). The location of nature conservation areas affected by fires (Emerald Network) is 425,000 hectares, of which 292,000 hectares (69 %) are in the territories with military operations and occupied territories.
3. *Economic restrictions.* Today, the rules for the implementation of forestry activities, in particular in the field of phytosanitary legality, are in force. During the war in Ukraine, the volume of illegally harvested wood remains consistently high, and such products will not be able to enter the EU market.
4. *Unsubstantiated and inappropriate closure of public access to some registers*: open register of logging tickets, including maps of quarter-separation division; public cadastral map; a layer with the boundaries of forests and objects of the nature reserve fund on the Ecosystem portal; a single registry for environmental impact assessment – materials for cases of deforestation, a single inspection portal.
5. *Improper ban on visiting forests where there were no hostilities.*

The above determines the need to define the priority directions for improving the management of the potential of forestry enterprises.

We believe that it is expedient to implement improvements both at the national level and at the level of individual enterprises. It is worth noting that certain changes are already taking place at the national level, considering the forest reform.

By the Resolution of the Cabinet of Ministers of Ukraine, "Some issues of reforming the management of the forest sector" [24], the state-specialised economic enterprise "Forests of Ukraine" was founded. Thus, there was a merger of specialised state forestry enterprises belonging to the sphere of management of the State Forestry Agency. The newly created enterprise "Forests of Ukraine" will be a joint-stock company. 100 % of the shares of this joint-stock company belong to the state.

The main advantages of creating a state enterprise "Forests of Ukraine" are as follows [25]:

- elimination of financial imbalances (equalisation of wages, increase of investment attractiveness of stagnant enterprises);
- management of forestry by EU standards and practices, resolution of the conflict of distribution of functions in the forestry sector (controlling - managing);
- increasing the investment attractiveness of the industry (credit resources, EU grants for the implementation of innovation and investment projects);
- detinization of the timber market, overcoming corruption, reducing illegal logging;
- use of modern information technologies for forest management;
- ensuring sustainable/efficient development of forestry.

We will present the consequences of implementing this reform through specific manifestations of the potential of forestry enterprises:

1. *Ecological potential.* The reform will allow for increasing the level of forest cover, mainly through implementing the President's Program "Green Country" and expanding the area of Ukraine's forests by 1 million hectares. Increasing forest cover will contribute to the achievement of UN Sustainable Development Goal 13 "Climate Action", and the EU Green Course Program to build a climate-neutral Europe by 2050. As a result, it will be possible to use forests tirelessly, that is, to optimize the use of wood and increase its in-depth processing.
2. *Production potential.* The creation of a single enterprise for the organization of cultivation, maintenance, and harvesting of forests will form the prerequisites for facilitating and expanding access to quality raw materials for Ukrainian wood processing enterprises.
   Simplifying the access of wood processing enterprises to forest raw materials will contribute to optimizing the use of wood and increasing its in-depth processing. This will make it possible to increase the added value created in the industry with smaller volumes of roundwood consumption.
3. *Labour potential.* Over the past 30 years, 60,000 workers have left the industry (62 % of the total workforce). Many enterprises need help to ensure stable functioning and employee confidence in the future, leading to layoffs. "Forests of Ukraine" will be able to provide the redistribution of labour resources, offering qualified workers positions throughout Ukraine with social security.
4. *Property potential.* The reform will create conditions for the renewal of fixed assets, the material and technical base, and the purchase of modern equipment, cars, and firefighting equipment for the protection and protection of forests. It will also create conditions for the restoration of forests and the increase of forest cover.

5. *Management potential.* The structure of "Forests of Ukraine" provides for the optimization of management personnel, which will free up funds for the payment of highly qualified forestry specialists in various production areas.
6. *Information potential.* Further digitalization of forestry enterprises' production processes will attract highly qualified specialists to production.

The Decree of the Cabinet of Ministers of Ukraine approved Ukraine's State Forest Management Strategy until 2035 [26]. According to the Strategy, the primary goal of a forestry enterprise is to build a transparent and effective enterprise management system for obtaining profit from economic activity. But the achievement of the goal must necessarily be accompanied by the preservation and increase of the country's natural resources and the sustainable development of forestry.

The main tasks of the forestry enterprise should be [26]:

- management of state property of permanent forest users, renewal of fixed assets and material and technical base of forestry enterprises, provision of enterprises with modern equipment for afforestation, and protection of forests, which are priority goals, with the aim of obtaining income for its owner – state;
- organization of forest management, safety, security, rational use and reproduction of forests;
- equalization of financial imbalances, increase of revenues to budgets of all levels;
- implementation of measures to preserve biodiversity in forests;
- conducting recreational activities;
- popularization among the population of the importance of conservation and rational use of forests;
- involvement of the public in the matter of forest reproduction and protection;
- ensuring equal opportunities, conditions and pay for women and men and actively encouraging women to participate at all employment levels.

While we believe that the mentioned reform will benefit the improvement of forestry enterprises management, there is still room for further progress on the national level. One of the ways of improvement is to intensify forest certification processes. According to Malek and Abdul Rahim [12], forest certification is the process of assessing the compliance of forest management with defined standards, which is carried out by independent certification organizations [12]. Such standards usually include economic, ecological, and social [13]. This process is voluntary, but it contributes to increasing the efficiency of forest resources management and positioning enterprises in ecologically sensitive markets. The two dominating in the world schemes of certification are the Programme for the Endorsement of Forest Certification Schemes (PEFC) and the Forest Stewardship Council (FSC) [12, 13].

The role of forest certification is essential due to the following facts:

- forest certification promotes environmental sustainability;
- acts as a tool for ecosystem services;
- influences the image of forest enterprises [12];
- promotes price premiums and improved market access [14].

Although there are studies that state that forest certification has limited effects [14], we believe it is an important tool for improving the forestry enterprises' potential management with a sustainability perspective.

It should be mentioned that the appropriate processes in Ukraine started in 2001, and as of December 21, 2022, more than 4 mln ha are FM-certified (forest management) by FSC (about 42 % of the total area of the forest) [27].

Zubizarreta et al suggest that forest certification can be promoted with the use of 5 mechanisms, 3 of which are external (market, signalling, and legal mechanisms), 2 are internal (learning and moral mechanisms) [13]. Thus, the mentioned mechanisms accompanied by balanced state policy in the sphere of forest certification will contribute to strengthening the respective processes, which in its turn will benefit both the sustainable development of the country and efficient forestry enterprises' potential management.

Another important way of increasing forestry enterprises' functioning efficiency is implementing the participatory approach, which involves local communities in forest management processes. In general, participatory forest management envisages engaging the local community to achieve sustainable forest management objectives [1]. We believe that the following measures can assist in involving local communities in achieving sustainable forest management:

- increasing the level of awareness of the local communities about the peculiarities of forest management based on sustainability and minimization of negative anthropogenic impact;
- popularization of a responsible and protective attitude to forest resources;
- involvement of local communities in environmental protection activities and environmental actions;
- implementation of a system of grant support for local initiatives aimed at forest conservation and rational forest use.

The participatory approach can be implemented in different forms, such as decentralized forest management, participatory forest management, joint forest management and community-based forest management [11]. The participatory approach is also promoted by forest certification [11].

One of the ways of participatory approach implementation is creating community forest enterprises, which will be able to meet economic, social and environmental challenges [10]. Such form of economic entities in the forestry sector will promote decentralization processes, but it also has disadvantages due to disbalances in the forestry sector of Ukraine. Thus, in our opinion, this direction of reform is currently not relevant enough in the conditions of Ukraine.

According to Mishenina and Dvorak [9], a participatory approach can be implemented through the public-private partnership mechanism. The authors state that the public-private partnership (PPP) mechanism is a perspective tool for economic and ecological policy implementation in the forestry sector under conditions of state and communal ownership of forests [9]. Considering the fact that 73 % of Ukrainian forests are in state ownership and 13 % are in communal ownership [6], implementation of PPP programs and mechanisms could benefit the effective functioning of the forestry enterprises and forest management as a whole.

PPP programs can contribute to efficient forest management in the following ways [9]:

- providing co-financing of projects, i.e. attracting investments to the forestry sector;
- distribution of risks between partners;
- distribution of responsibility between partners.

It should be mentioned that there is a variety of forms of PPP, which expands the possibilities of using this tool in various situations. Mishenina and Dvorak define that the agreements between forestry and recreational forest protection subcomplexes should be considered [9]. Another issue that can be solved within PPP programs, in our opinion, is the proper implementation of the forest silvicultural system. Scientists define that a continuous cover forestry system is the one that benefits both ecological and economic aspects of forest management [7]. Such a system envisages that the next generation of trees is established before the final crop trees have reached the optimal rotation period [7]; this promotes the balanced forest use mechanisms and contributes to the sustainable development of the country as a whole.

To conclude the main aspects related to the rational level of forest management, we believe it is important to identify key issues of the respective sphere. According to Pietarinen et al the dominant issues are: ecological modernization, civic environmentalism, and green governmentality [2].

In order to determine the ways of forestry enterprises' potential management improvement at the level of individual enterprises, it is necessary to conduct an appropriate analysis. To define priority measures for the improvement of forestry enterprises management, we find it expedient to identify key factors of impact on the basis of correlation and regression analysis. Net profit of the forestry enterprises was chosen as a dependent variable (Y), as the respective indicator is an absolute measure of business entities' performance. We believe that such choice of the dependent variable is due to its particular importance from the enterprise development perspectives standpoint. It is the net profit which reflects the internal capabilities of the enterprise to provide necessary funding for the development initiatives. Thus, we consider it expedient to analyze the impact of individual factors on the formation of the net profit. As the independent variables the following indicators were chosen:

X_1 – fixed assets to current assets ratio;
X_2 – fixed assets turnover;
X_3 – current assets turnover;
X_4 – ratio between receivables and payables;
X_5 – operating cycle duration, days;
X_6 – labour productivity, ths. UAH / person;
X_7 – net revenue growth rate;
X_8 – material capacity;
X_9 – sales profitability;
X_{10} – current ratio;
X_{11} – cash ratio;
X_{12} – financial leverage.

The choice of the mentioned above indicators is defined by the fact that they represent, in our opinion, key aspects of resource provision and the financial condition of the forestry enterprise. Another factor that impacts the selection of the mentioned criteria is the availability of the data. All necessary data for calculating the relevant indicators are contained in the official financial statements of enterprises. So, we can conclude that the choice of the independent variables meets the following requirements:

- the indicators in complex reflect the main directions of the resource provision of the forestry enterprises (e.g. technical, material, human resources);
- the main complements of the financial state such as stability, profitability, and economic activity are characterized within the chosen indicators;
- the data for calculating and analysis of the mentioned above indicators are available in the financial statements of the enterprises.

In the next step, we will form the observation base for correlation and regression analysis. As the research objects, 10 forestry enterprises of the Polissia region were chosen. Within the framework of this research, the following oblasts belong to the Polissia region: Volyn (SE "Horodotske forestry", SE "Manevytske forestry"), Rivne (SE "Bereznivske forestry", SE "Sarnenske forestry"), Zhytomyr (SE "Bilokorovytske forestry", SE "Korostenske forestry"), Kyiv (SE "Bohuslavske forestry", SE "Teterivske forestry"), and Chernihiv (SE "Horodnianske forestry", SE "Chernihivske forestry"). The observation period is 2019-2021. Such observation period is determined due to the fact that financial statements of the enterprises for 2022 were not formed and publicized at the time of the research. At the same time, the selected period covers 2019 (the pre-crisis period due to the COVID-19 pandemic), 2020 (the crisis period), and 2021 (the period of overcoming the consequences of the crisis). Thus, the total number of observations is 30, which ensures the representativeness of the raw data for correlation and regression analysis.

The initial data for the analysis are presented in table 2.

According to the calculated data, we can note some common trends in the development of forestry enterprises:

- during 2019-2020, in the activity of the vast majority of the analyzed enterprises, a reduction in activity volume is observed, while in 2021, there is a substantial increase;
- high degree of production costs capacity of the enterprises' activity;
- a sufficient level of liquidity;
- current assets mostly dominate the structure of assets.

It should be mentioned that a high level of cost capacity is considered by scientists as one of the most crucial factors influencing the forestry enterprises functioning [15].

The next step is to analyze the factors from the interrelationship point of view, as well as to perform a multicollinearity test. The results of the correlation analysis are presented in the matrix of pair correlations (table 3).

According to the data presented in table 3, we must note that there is a relationship of varying degrees between the dependent and independent variables. The strongest (highest) level of influence on the formation of the net profit indicator (Y) is determined by factor X_6 (labour productivity). Independent variables X_5 (the operating cycle duration) and X_7 (net revenue growth rate) are also marked by a substantial degree of connection. It is worth noting that according to the multicollinearity test, there is a substantial degree of connection between X_6 and X_7 factors, but we believe it is appropriate to leave both factors for further consideration.

The equation formed by the results of regression analysis is the following:

$$Y = -6359.68 - 82.07X_5 + 12.74X_6 + 4938.27X_7, \tag{1}$$

where Y – net profit, ths. UAH, X_5 – the operating cycle duration, days, X_6 – labour productivity, ths. UAH / person, X_7 – net revenue growth rate, coefficient.

According to the regression equation parameters, the determination coefficient $R^2 = 0.7$; that is, 70 % of the variance of the values of the dependent variable (net profit) is explained by the obtained equation. It should be mentioned that the relatively low level of determination coefficient is due to the fact that net profit formation, in addition to the internal factors analyzed in the model, is influenced by a significant number of external factors, for example, the exchange rate volatility, the balance of the foreign trade balance, the international policy of the government, the level of inflation, etc. Thus, we believe that for the purposes of the current research aimed at improvement of forestry enterprises internal management, the value of the determination coefficient is sufficient. According to the results of the F-test (Fisher's test), the constructed model is considered adequate for the sample data because $F_{fact}(20.17) > F_{crit}(3.35)$ (with a probability of error of 0.05).

Thus, as a result of the built model, we can highlight key directions for increasing the efficiency of the functioning of forestry enterprises in terms of the formation of net profit:

- reducing the duration of the operating cycle;
- increasing the level of labour productivity;
- ensuring the growth of net revenue at progressive rates.

The basic activities within forest management include the following: technological activities, quality activities, transport activities, storage, and delay [8]. That means that the mentioned

Table 2. Initial data for correlation and regression analysis of forestry enterprises.

Years	Y	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}	X_{12}
SE “Horodotske forestry”													
2019	330	0.81	6.41	5.19	0.70	29.67	540.22	0.92	0.22	0.21	11.27	7.05	0.10
2020	758	0.74	6.67	4.92	0.63	24.27	561.11	0.91	0.23	0.19	13.29	9.37	0.09
2021	4999	0.72	9.48	6.80	0.20	12.12	925.96	1.65	0.14	0.29	7.38	5.95	0.32
SE “Manevytske forestry”													
2019	865	2.36	4.33	10.21	0.36	22.99	381.96	0.89	0.22	0.14	1.20	0.21	0.29
2020	2096	2.73	4.37	11.93	0.20	18.07	419.99	0.94	0.18	0.15	1.56	0.99	0.23
2021	25217	1.82	6.54	11.93	0.22	8.64	809.49	1.59	0.11	0.34	2.82	2.06	0.42
SE “Bereznivske forestry”													
2019	2673	3.04	5.23	15.9	0.22	22.26	532.90	0.92	0.49	0.21	0.54	0.01	1.76
2020	3160	3.94	5.23	20.61	0.07	16.34	548.05	1.00	0.45	0.81	0.45	0.07	1.51
2021	9862	2.58	6.70	17.27	0.15	13.16	805.54	1.42	0.39	0.23	1.26	0.57	2.01
SE “Sarnenske forestry”													
2019	4445	1.80	6.58	11.82	0.59	19.50	708.54	0.94	0.48	0.23	1.24	0.40	0.43
2020	2522	1.49	6.90	10.3	0.08	15.77	704.89	0.99	0.47	0.19	1.68	1.27	0.43
2021	23437	0.90	9.87	8.89	0.15	89.71	1145.17	1.57	0.37	0.28	1.92	1.47	0.88
SE “Bilokorovytske forestry”													
2019	574	0.66	10.17	6.68	0.50	43.32	332.36	0.93	0.39	0.16	1.30	0.08	1.01
2020	138	0.52	9.54	4.97	0.25	67.74	311.31	0.92	0.43	0.13	1.26	0.07	1.11
2021	1981	0.89	9.26	8.22	0.15	40.95	441.28	1.52	0.34	0.14	0.69	0.01	1.46
SE “Korostenske forestry”													
2019	6157	3.63	4.00	14.52	0.52	17.36	557.03	0.88	0.58	0.18	1.15	0.50	0.35
2020	1731	2.07	4.06	8.42	0.82	22.72	585.65	0.80	0.64	0.16	3.10	1.61	0.13
2021	14604	1.77	6.53	11.56	0.23	12.79	1204.76	1.76	0.66	0.26	1.42	0.91	0.34
SE “Bohuslavske forestry”													
2019	1139	0.51	8.71	4.44	0.14	32.25	358.75	0.93	0.25	0.21	1.52	0.97	0.79
2020	1150	0.38	9.21	3.48	0.24	38.32	386.01	0.86	0.37	0.21	1.67	1.02	0.87
2021	5249	0.31	14.64	4.51	0.09	26.25	667.54	1.89	0.32	0.27	1.23	0.84	1.62
SE “Teterivske forestry”													
2019	3175	0.50	7.76	3.87	1.21	40.97	764.61	0.80	0.22	0.25	3.43	1.68	0.26
2020	1232	0.36	9.04	3.23	0.45	45.39	887.97	0.95	0.19	0.20	2.85	1.92	0.37
2021	23582	0.29	14.77	4.27	0.19	28.36	1691.24	1.85	0.12	0.33	1.82	1.16	0.76
SE “Horodnianske forestry”													
2019	225	0.55	9.16	5.02	0.65	60.35	335.98	0.93	0.12	0.11	2.50	0.28	0.37
2020	275	0.46	10.93	5.07	0.42	59.63	360.91	1.02	0.27	0.10	2.58	0.45	0.37
2021	2006	0.56	14.01	7.89	0.18	37.31	558.23	1.46	0.21	0.13	2.26	0.36	0.35
SE “Chernihivske forestry”													
2019	150	1.72	4.33	7.47	0.32	44.86	358.64	0.82	0.31	0.15	1.03	0.09	0.50
2020	568	1.70	5.01	8.53	0.06	39.59	507.00	1.19	0.39	0.15	0.94	0.01	0.72
2021	10091	1.59	7.61	12.11	0.03	22.79	860.39	1.89	0.20	0.24	0.84	0.28	0.382

Table 3. Matrix of pair correlations of independent variables.

	Y	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}	X_{12}
Y	1.00												
X_1	0.04	1.00											
X_2	0.21	-0.74	1.00										
X_3	0.20	0.91	-0.54	1.00									
X_4	-0.27	-0.16	-0.19	-0.33	1.00								
X_5	-0.53	-0.53	0.32	-0.60	0.25	1.00							
X_6	0.80	-0.10	0.31	0.04	-0.14	-0.48	1.00						
X_7	0.68	-0.18	0.52	0.07	-0.55	-0.36	0.67	1.00					
X_8	-0.10	0.47	-0.38	0.43	0.00	-0.20	-0.07	-0.19	1.00				
X_9	0.34	0.38	-0.05	0.48	-0.23	-0.45	0.33	0.22	0.06	1.00			
X_{10}	-0.13	-0.30	-0.02	-0.36	0.42	-0.07	0.03	-0.12	-0.32	-0.06	1.00		
X_{11}	-0.02	-0.26	-0.04	-0.30	0.31	-0.23	0.14	-0.03	-0.30	0.03	0.98	1.00	
X_{12}	0.09	0.19	0.20	0.38	-0.51	-0.04	-0.02	0.28	0.23	0.31	-0.47	-0.43	1.00

above directions should be implemented within each and every basic activity to achieve the proper result and to increase the efficiency of forestry enterprises' functioning.

The next step of our study is to identify key measures of forestry enterprises' potential management improvement according to the defined impact factors.

1. *Reduction of the duration of the operating cycle.*

The duration of the enterprise's operating cycle is an indicator of the rhythm of all business processes of the forestry enterprise, which is ensured by the action of internal and external environmental factors. According to the National Accounting Regulation (Standard) 1 "General Financial Reporting Requirements" [28], the operating cycle is interpreted as the time interval between the acquisition of stocks for the implementation of activities and the receipt of funds (cash equivalents) from the sale of products or goods and services produced from them.

The shortening of forestry enterprise operating cycle can be achieved through the reduction of the terms of turnover of assets, particularly in the part of stocks and receivables. Shortening the operating cycle leads to more stable financing of the company's current activities. Sufficient financing creates conditions for the uninterrupted supply of materials to the production process, which means the optimization of the duration of the production process and the sale of products based on high quality and the use of existing competitive advantages on the market. In turn, selling products should be accompanied by a rational policy of managing the company's receivables.

Forestry enterprises can achieve a decrease in turnover time of current assets under the following conditions:

- implementation of economically justified stock norms;
- compliance with the principle of optimal price-quality ratio when forming stocks;
- improvement of logistics management and improvement of the sales policy of enterprises;
- intensive reproduction of the elements of the property potential of the enterprise;
- active introduction of aspects of the circular economy on the ground in forestry;
- 100 % implementation of certification of forestry enterprises;
- study of the product structure and increase in the specific weight of products of high demand;

- effective management of receivables (control over the occurrence and state of receivables at each stage of the implementation of management decisions; control of settlements with debtors for deferred and overdue debts);
- building a rational system of interaction with banks regarding the attraction of funds and the implementation of settlements, and the implementation of optimal credit policy;
- constant monitoring and improvement of the company's settlement system.

The strategic management of the operating cycle requires a separate study. In forestry, the operating cycle includes economic operations for reproducing and harvesting forest resources. Growing such assets exceeds one operating cycle and is 50-70 years.

2. *Increasing labour productivity.*

Savings in the consumption of current assets helps to improve the use of production facilities and increase labour productivity. Scientific, technical, organizational, structural and socio-economic changes are classical factors of labour productivity improvement. Personnel turnover and the problem of HR policy of forestry enterprises require balanced management steps to increase labour productivity. The war in Ukraine complicates the situation.

So, forestry enterprises can take following steps in this sphere:

- make structural changes in production;
- improve the material and technical level of activity and production;
- improve management, organization of production and labour (improvement of the structure and rational distribution of management functions, social protection of employees, increase of the wage fund);
- increase in production and sales volumes (management and structural reform of forestry enterprises along with a relative reduction of employees);
- diversifying forestry enterprises' activities (expanding areas of activity and searching for new types of activities).

3. *Ensuring the growth of net income at progressive rates.*

The proposals summarized by us from the point of view of shortening the operating cycle and increasing labour productivity in the complex may be effective for the growth of the net income of forestry enterprises. This indicator is a marker of the financial and economic condition of the forestry enterprise. Also, the indicator reflects the level of economic security of the enterprise. Diversification of the activities of forestry enterprises is one of the ways of achieving the growth of net income at a faster pace. One of the options for diversification is the cultivation of energy crops on forestry lands that cannot be used for other needs and the subsequent production of products from the corresponding crops [18]. This measure will contribute not only to the better use of forest resources but also will generate an additional flow of income for the enterprise.

Another important issue to be addressed for the efficient functioning of forestry enterprises is their adaptation to the conditions of the external environment. As we mentioned earlier, the process of functioning of forestry enterprises and the process of their net profit formation, in particular, are being influenced by a large variety of external factors. Thus, it is essential to form the mechanism of enterprise interaction with the environment. Such a mechanism will benefit not only to efficient functioning of the forestry enterprises, but also to reducing the negative anthropogenic influence on the environment [29].

6. Conclusions

As the result of the conducted research, we can conclude the following.

1. Forest is an extremely important resource that not only ensures the livelihood of mankind but is also a source of renewable resources under conditions of balanced environmental management. Forest ecosystems create conditions for people's lives, thus forming a critically important foundation for ensuring the sustainable development of any country. The forests of Ukraine cover 15.9 % of the territory, providing economic, ecological and social functions. Efficient functioning of the forestry enterprises contributes to the sustainable development of the country due to the performed functions.
2. Negative trends have been observed in recent years related to deforestation, forest degradation, and a decrease in the efficiency of forestry enterprises functioning. The existing crisis trends in the forestry sector have significantly deepened as a result of the full-scale war on the territory of Ukraine, which necessitates the implementation of measures to improve the management of the potential of forestry enterprises. The main problematic issues related to the consequences of the full-scale war are the following: the difficulty of demining de-occupied territories; forest fires, economic restrictions, inappropriate closure of public access to some registers, improper ban on visiting forests where there were no hostilities. These and other threats to the efficient functioning of the forestry enterprises define the necessity of improvement of the existing enterprise management mechanism in the relevant sector of economic activity.
3. Considering the complexity of the problems related to effective forest management, we are convinced that measures to increase the efficiency of the use of the forestry enterprises' potential should cover both the national level and the level of individual economic entities. It is worth noting that at the national level, there are already changes related to forestry sector reform. In particular, the creation of the state enterprise "Forests of Ukraine" will contribute to a balanced approach in the field of forest management. At the same time, we believe that it is possible to expand the priority directions of state policy in the specified area with the measures related to enhancing certification processes, as well as implementing a participatory approach in forest management.
4. To determine the measures that should be implemented to improve the enterprise potential management system at the level of individual enterprises, the method of correlation and regression analysis was used. The observation base was formed by data for 2019-2021 on 10 forestry enterprises in the Polissia region. The net profit was chosen as a dependent variable as it is the indicator which reflects the economic result of the enterprise functioning. The conducted analysis made it possible to detect that the key internal factors of influence on the net profit, thus, on the efficiency of the enterprise, are as follows: the operating cycle duration, labour productivity, net revenue growth rate.
5. Based on the analysis, it was found that priority measures should include reducing the duration of the operating cycle, increasing labour productivity, and ensuring high rates of net income growth. Key measures within each of the considered directions are proposed. Considering the caveats on the model of the dependence of net profit on internal factors, it was determined that an important direction of increasing the efficiency of management of the forestry enterprises' potential is also ensuring the mechanism of interaction with the environment.
6. The prospects for further research lie in the definition of strategic measures in the identified areas (in particular, regarding the management of the duration of the operating cycle), as well as in the study of the influence of external factors on the activities of forestry enterprises.

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References

[1] Tessema S B and Nayak D 2022 *Trees, Forests and People* **9** 100318 URL https://doi.org/10.1016/j.tfp.2022.100318
[2] Pietarinen N, Harrinkari T, Brockhaus M and Yakusheva N 2023 *Forest Policy and Economics* **147** 102897 URL https://doi.org/10.1016/j.forpol.2022.102897
[3] 2022 Forests for Climate: Scaling up Forest Conservation to Reach Net Zero White Paper World Economic Forum Cologny/Geneva URL https://www.weforum.org/whitepapers/forests-for-climate-scaling-up-forest-conservation-to-reach-net-zero/
[4] United Nations 2023 The 17 Goals | Sustainable Development URL https://sdgs.un.org/goals
[5] Zheng M, Liu Y and Zhou R 2022 Sustainable Development of Forest Management – Transition Point Analysis Based on Forest Value Assessment *Proceedings of the 3rd International Conference on Green Energy, Environment and Sustainable Development (GEESD2022)* (*Advances in Transdisciplinary Engineering* vol 23) ed Zhang X *et al.* (IOS Press) pp 740–746 ISBN 9781643683126 URL https://doi.org/10.3233/ATDE220348
[6] State Forest Resources Agency of Ukraine 2022 General characteristics of Ukrainian forests URL https://forest.gov.ua/en/areas-activity/forests-ukraine/general-characteristic-ukrainian-forests
[7] Knoke T, Paul C, Gosling E, Jarisch I, Mohr J and Seidl R 2023 *Environmental and Resource Economics* **84**(2) 343–381 ISSN 1573-1502 URL https://doi.org/10.1007/s10640-022-00719-5
[8] Malindzakova M, Malindzak Jr D and Garaj P 2021 *TEM Journal* **10**(3) 1319–1324 URL https://doi.org/10.18421/TEM103-40
[9] Mishenina H and Dvorak J 2022 *Administrative Sciences* **12**(4) 156 URL https://doi.org/10.3390/admsci12040156
[10] Piabuo S, Hoogstra-Klein M, Ingram V and Foundjem-Tita D 2022 *Forest Policy and Economics* **135** 102664 URL https://doi.org/10.1016/j.forpol.2021.102664
[11] Degnet M B, van der Werf E, Ingram V and Wesseler J 2022 *Forest Policy and Economics* **143** 102815 URL https://doi.org/10.1016/j.forpol.2022.102815
[12] Malek E J and Abdul Rahim A R 2022 *Trees, Forests and People* **10** 100331 URL https://doi.org/10.1016/j.tfp.2022.100331
[13] Zubizarreta M, Arana-Landín G and Cuadrado J 2021 *Journal of Cleaner Production* **294** 126267 URL https://doi.org/10.1016/j.jclepro.2021.126267
[14] Villalobos L, Coria J and Nordén A 2018 *Land Economics* **93** URL https://doi.org/10.3368/le.94.2.220
[15] Shvets M, Markov F, Fitisov A and Didenko P 2020 *Scientific Horizons* (6(91)) 92–100 URL https://doi.org/10.33249/2663-2144-2020-91-6-92-100
[16] Furdychko O, Drebot O, Palianychko N, Dankevych S and Okabe Y 2021 *Agricultural and Resource Economics* **7**(4) 218–244 URL https://doi.org/10.51599/are.2021.07.04.12
[17] Tsehelnyk N I 2021 *Agrosvit* (13-14) 17–24 URL https://doi.org/10.32702/2306-6792.2021.13-14.17
[18] Diadchenko I and Sakharnatska L 2021 *Agroecological Journal* (1) 205–211 URL https://doi.org/10.33730/2077-4893.1.2021.227853
[19] State Forest Resources Agency of Ukraine 2020 Public report of the head of the State Forest Resources Agency of Ukraine for 2019 URL https://forest.gov.ua/storage/app/sites/8/%D0%BF%D1%83%D0%B1%D0%BB%D1%96%D1%87%D0%BD%D1%96%20%D0%B7%D0%B2%D1%96%D1%82%D0%B8/publichniy-zvit-dalru-za-2019-rik.pdf
[20] State Forest Resources Agency of Ukraine 2021 Public report of the head of the State Forest Resources Agency of Ukraine for 2020 URL https://forest.gov.ua/storage/app/sites/8/%D0%BF%D1%83%D0%B1%D0%BB%D1%96%D1%87%D0%BD%D1%96%20%D0%B7%D0%B2%D1%96%D1%82%D0%B8/publichniy-zvit-derzhlisagentstva-za-2020.pdf
[21] State Forest Resources Agency of Ukraine 2022 Public report of the head of the State Forest Resources Agency of Ukraine for 2021 URL https://forest.gov.ua/storage/app/sites/8/%D0%BF%D1%83%D0%B1%D0%BB%D1%96%D1%87%D0%BD%D1%96%20%D0%B7%D0%B2%D1%96%D1%82%D0%B8/publichniy-zvit-za-2021.pdf
[22] International Renaissance Foundation 2023 EU4USociety project URL https://www.irf.ua/en/program/eu4usociety-en/
[23] WWF-Ukraine 2022 What should forest management look like during the war and post-war reconstruction? URL https://wwf.ua/?7610441/forest-restoration-war-time

[24] Cabinet of Ministers of Ukraine 2022 Some issues of reforming the management of the forest industry URL https://www.kmu.gov.ua/npas/deiaki-pytannia-reformuvannia-uprav-a1003
[25] State Forest Resources Agency of Ukraine 2022 Experts analyzed the scenarios of forest sector reform URL https://forest.gov.ua/news/eksperty-proanalizuvaly-stsenarii-reformuvannia-lisovoi-haluzi
[26] Cabinet of Ministers of Ukraine 2021 State strategy for forest management of Ukraine until 2035 URL https://zakon.rada.gov.ua/laws/show/en/1777-2021-%D1%80#Text
[27] FSC Ukraine 2023 FSC Facts & Figures in Ukraine URL https://ua.fsc.org/ua-en/fsc-facts-figures-in-ukraine
[28] Ministry of Finance of Ukraine 2013 On the approval of the National regulation (standard) of accounting 1 General requirements for financial reporting URL https://zakon.rada.gov.ua/laws/show/z0336-13?lang=en#Text
[29] Ostapchuk T P, Lehenchuk S F, Denysiuk O H, Orlova K Y and Biriuchenko S Y 2022 *IOP Conference Series: Earth and Environmental Science* **1049** 012043 URL https://doi.org/10.1088/1755-1315/1049/1/012043

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Harmonization of investment and operational costs of the grain industry in the light of the theory of sustainable development

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Harmonization of investment and operational costs of the grain industry in the light of the theory of sustainable development

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Abstract. Approaches to harmonization of methods for determining the optimal level of investment in the renewal of the fleet of combine harvesters and current expenses of agricultural enterprises under conditions of implementation of sustainable development goals in the activities of economic entities are investigated. It is established that the implementation of the concept of sustainable development for the domestic agricultural sector intensifies the processes in it, brings to the fore the problems of ensuring food security of the State, increasing the production of safe products while preserving landscapes and minimizing anthropogenic pressure. At the same time, the seizure of part of the territory, mining of the liberated and adjacent to the combat zone areas raises the issue of rational use of land resources. Under such conditions, only further introduction of innovations aimed at increasing yields and the use of intensive technologies is the most important vector for the development of domestic agriculture. This places strict requirements on the technical condition of its resource potential. Unfortunately, the unsatisfactory technical condition of the grain harvesting machinery fleet and its destruction as a result of hostilities exacerbate the problem of technical support for grain production, in particular for harvesting. Under such conditions, an important task is to develop methodological techniques for determining the optimal, harmonized values of investments in the reproduction of resource potential and operating costs. The tested methodological approach allows determining the optimal level of investment in the renovation of the combine harvester fleet, taking into account the peculiarities of wheat production organization, grain price conditions, material resources, harvesting equipment, and financial factors. The calculations showed that it is economically inexpedient to invest in the renewal of the combine harvester fleet using the most common combine harvester models if one unit has less than 600 hectares of wheat crops. A positive feature of the tested approach is the ability to minimize unproductive costs by taking into account technological and market factors in determining the optimal level of costs. Instead, the introduction of innovations leads to a change in the form of the production function, which should affect the dynamics of the marginal efficiency of investments, and therefore it is promising to expand approaches to modeling and take into account the role of innovations in finding the optimal level of current costs and investments.

1. Introduction

The functioning of the agrarian sector on the basis of sustainable development implies that it provides three interrelated functions: economic (providing income to agricultural producers), social (ensuring food security, providing productive employment, improving the quality of life) and environmental (maintaining biodiversity, preserving the integrity of the agricultural landscape, soil fertility, clean air and water resources) [1]. Understanding the role of the agricultural sector, in particular the grain industry, through the prism of the Sustainable Development Goals [2] allows us to consider the latter as a guarantor of the country's economic and food security. Ensuring the sustainability of agricultural production and the realization of its social function determines the increase in grain production, which places strict requirements on the fleet of combine harvesters. Problems in this area have been repeatedly discussed during discussions on the prospects for the development of the agricultural sector. In particular, it is worth mentioning the 2.5-fold reduction in the fleet of combine harvesters of Ukrainian agricultural enterprises during 2000-2020, which led to a permanent increase in the amount of operating hours per unit. As a result, the workload per combine harvester reached almost 200 hectares at the end of 2020, while in Germany and France in 2016-2020 it did not exceed 60-70 hectares of wheat crops.

The problem can be solved by simultaneously increasing investments in the renovation of the grain harvester fleet and obtaining harvesting equipment on a land-list basis. The drop of more than 30% in gross domestic product significantly limits the investment opportunities of agricultural companies and significantly increases the cost of borrowed resources. Under such conditions, it is particularly important to justify approaches to determining the optimal level of capital expenditures and their harmonization with the level of current costs caused by the technological process.

Sustainable development is a basic concept for business and policy development that reflects the understanding that progress is impossible without addressing pressing environmental issues such as ecosystem degradation and climate change. This implies that society can only develop on the basis of meeting the needs of the present while protecting the livelihoods of present and future generations [3]. Since the laws of nature and social development are unchanging and immutable [4], the solution is for society to respect the limits of "safe workspace" [5, 6] and limit environmental damage [7]. Although "sustainability is a pluralistic concept" [8], in a broad sense it focuses on simultaneously ensuring economic growth, societal prosperity, and environmental protection [9]. In this sense, the concept of sustainable development integrates economic, social, and environmental concerns and offers a new way of thinking that recognizes the world as interconnected between nature, society, and the economy [10].

It should be noted that population growth and changes in the structure and volume of consumption cause an increase in anthropogenic pressure [11]. Sustainable land use can reduce the negative impact of these stressors. The Sustainable Development Goals (SDGs) were formulated in 2015 to meet the demands of the present, and they enshrine the commitment of developed countries to end poverty and hunger by 2030. However, climate change poses a challenge to achieving these goals, as slow processes of environmental change, increased climate variability, and extreme weather events negatively affect agricultural productivity [2]. That is why innovation strategies, in particular agricultural innovation systems (AIS), are key examples of potential ways to improve the economic, environmental and social performance of the agricultural sector. Not only because agriculture contributes about 30% of the world's gross domestic product and has a high return on investment [12], but also because of the long-term positive impact of agricultural research and development (R&D) on productivity growth, and because new technological solutions contribute to the sustainable use of natural resources. Nevertheless, agriculture receives about 5% of R&D investments [13].

In turn, an important economic problem in economics and econometrics research is the substantiation of approaches to determining the economic and environmental optimum of operating (technological) and capital costs in the context of rapid implementation of R&D results. A significant contribution in this area has been made by scientists who have studied the use of production functions. In particular, we note the works devoted to the identification of production functions [14–19]. Secondly, studies on industrial organization [20], trade [21–24] and international economics [25], which aim to measure productivity [26], returns to scale, and more recently, prices [16, 27, 28] using production functions. Third, a significant contribution has been made in works that focus on the development of methods for estimating multi-product production functions [29–33]. And fourth, a whole area of macroeconomic literature, starting with [34], is devoted to the issues of uncertainty in product prices. The approaches of these authors are based on the assumption of the form of the production function, which allows its identification [35].

Investment is a continuous, systematic activity that focuses on the entire organization, including its forms and methods [36]. Investing in innovation determines the ability of an agricultural enterprise to maintain competitive advantage and better respond to rapid market and economic changes [37–40]. This process is based on the use of tools and measures that are important for the transition of society and the economy to sustainable development [41, 42]. Recognition of agricultural innovation as a driving force for addressing environmental issues and social inequalities has led to the emergence of sustainable entrepreneurship in the agricultural sector [43]. Sustainable entrepreneurship encompasses business entities that can achieve profitability by exploiting environmental market gaps [44]. They address social and environmental challenges through a business approach based on human values and go a step further to mitigate the impact of economic crises while promoting economic growth and social equity [45, 46].

However, today's challenges, in particular the complexity and, in some aspects, the impossibility of predicting the development of economic processes, make it important to study approaches to determining the optimal level of investment and their harmonization with the level of current costs of agricultural enterprises.

2. Results and discussion

The functioning of the agrarian sector on the basis of sustainable development, the realization of its economic and social function, overcoming the challenges caused by the actions of the aggressor, leads to a reorientation of approaches to modeling technological processes to effective principles, maximizing production and profit. In view of this, nonlinear production functions that maximize the output or added value were chosen as the methodological basis for modeling the cost optimum. In turn, there is a need to harmonize approaches to determining the optimal amount of operating costs that maximizes output with the amount of investment to restore the resource potential damaged as a result of hostilities. The harmonization of economic processes is usually interpreted as their mutual coordination, systematization, unification, coordination, streamlining, and compliance. Harmonization of economic processes helps to balance the functioning of a business entity. Its systemic vision switches to the coordination of the formation and use of its resource potential, investment and operating costs. Thus, the methodological basis of our study is a system of models that allows harmonizing the ratio of operating expenses and capital investments.

The first step towards solving the problem was to determine, based on the statistical processing of the 2020 reports of Ukrainian agricultural enterprises, the equation of dependence of wheat yield on variable costs per hectare of harvested area:

$$f_1(x) = -0.180x^2 + 6.425x, \tag{1}$$

where $f_1(x)$ – is the expected yield of wheat, tons/ha; x – variable production costs per 1 ha of harvested wheat area, UAH thousand.

The dependence has a high level of statistical reliability, as evidenced by the value of the coefficient of determination (R^2), which for function (1) is 0.9106, as well as the excess of the calculated value of the Fisher coefficient ($F_p = 28.0$) over its tabular value ($F_{tab} = 0.116$). At the same time, based on the values of the Student's t coefficient, the coefficients for the linear and quadratic terms of the formula (1) were also highly reliable. In particular, with the tabular value of this coefficient from -1.72 to 1.72, its actual values with the specified members were equal to 3.2 and 6.17, respectively.

The relevance of the application of function (1) for planning calculations ensures compliance with the optimal wheat harvesting terms, which in the case of single-phase (direct) harvesting should not exceed 6-10 days after the wheat reaches full maturity. At the same time, an analysis of the conditions and timing of early grain harvesting in 2016-2020 shows that due to the insufficient quantity and unsatisfactory technical condition of most of the grain-harvesting equipment, its duration was from 32 to 55 days [47]. At the same time, the extension of the duration of the harvesting campaign beyond a ten-day period caused a daily decrease in productivity by 1% [48], as a result of which more than 10% of the potential harvest, i.e. 6-6.5 million tons of grain, was lost.

Considering this circumstance, the question arose – is it possible, by slightly reducing the expected level of yield and the planned level of costs, to minimize crop losses and maximize the financial result, and how to implement such an approach in the production function (1). To solve it, a component was introduced to equation (1), which allows to adjust the expected potential yield by the amount of potential losses, proportional to the duration of the harvesting campaign (d). Taking this into account, the modified form of function (1) is as follows:

$$\begin{aligned} f_2(x,d) &= (-0.180x^2 + 6.425x) - 0.01(d-10)\cdot(-0.180x^2+6.425x) = \\ &= (1.1-0.01d)\cdot(-0.180x^2+6.425x), \end{aligned} \tag{2}$$

where $f_2(x,d)$ – is the expected yield of wheat, tons/ha; x – variable production costs per 1 ha of harvested wheat area, UAH thousand; d – duration of the collection campaign, days.

In the future, functions (1) and (2) were combined into a system that allows you to determine the expected yield in the event that the harvesting campaign ends in the optimal agrotechnical period or in the event that it is extended beyond a ten-day period:

$$f_3(x,d) = \begin{cases} (-0,180x^2 + 6,425x) \text{ if } d \leq 10 \\ (1,1–0,01d)\cdot(-0,180x^2+6,425x) \text{ if } d \geq 10, \end{cases} \tag{3}$$

where $f_3(x,d)$ – is the expected yield of wheat, tons/ha; x – variable production costs per 1 ha of harvested wheat area, UAH thousand; d – duration of the collection campaign, days.

The inclusion of the variable d in function (2) necessitated the formalization of approaches to calculating the latter. It is logical to calculate it through the ratio of the expected gross harvest and the total productivity of the combine harvester fleet of the agricultural enterprise. In turn, the expected gross yield is the product of the sown area and the planned yield. The latter, for modeling purposes, can be determined using function (1). In the meantime, the total productivity of the farm's combine harvester fleet is determined by their number, hourly productivity, and shift duration. At the same time, to take into account the production conditions and the technical condition of combine harvesters, it is advisable to introduce a shift time efficiency factor:

$$d(pl,x,k) = \frac{pl\cdot f_1(x)}{k\cdot W_{hour}\cdot T_{zm}\cdot K_{vrch}}, \tag{4}$$

where pl – is the area from which wheat was harvested, ha; $f_1(x)$ – expected yield of wheat, tons/ha; W_{hour} – hourly productivity of the grain harvester, centner per hour; T_{zm} – shift duration, hours (according to [49–51] the recommended value is 12.0 hours); K_{vrch} – coefficient of use of the working time of the shift (according to [49–51] the recommended value is 0.7);k – is the number of grain harvesting units, units.

Taking into account the purely individual nature of the formation of the size of wheat sowing areas and the fleet of combine harvesters for each agricultural enterprise, their ratio in formula (4) was replaced by the planned area of wheat threshing by one combine harvester (N):

$$d(x, N) = \frac{N \cdot f_1(x)}{W_{hour} \cdot T_{zm} \cdot K_{vrch}}, \tag{5}$$

where N – is the planned area of wheat threshing by one combine harvester, ha.

After that, based on the analysis of statistical reports, it was determined that domestic grain producers mainly have units with an engine power of 330-335 hp. The analysis of the market of grain harvesting equipment shows that the closest to the indicated capacity are the sixth class combines widely represented on it – *New Holland CR7.90*, *John Deere S670*, *John Deere S770*, *CASE IH 7140*, *CASE IH 7240*, *Gleaner S97*, *Claas Lexion 740*, *Massey Ferguson 9540*, *Massey Ferguson 9545* [52]. With this in mind, based on the analysis of the offer of aggregates from this list on the Tractorhouse.com website [53], the model with the largest number of lots – *John Deere S670*, which has a nominal engine power of 317 hp – was chosen as the base model with hourly productivity of 111.27 centner per hour.

Further, by substituting into function (5) the actual and recommended values of the hourly productivity of the John Deere S670 combine (111.27 t/ha), the duration of the shift (12 hours), the coefficient of utilization of the working time of the shift (0.7), an analytical expression was formed functions of the dependence of the duration of the harvesting campaign on the planned threshing area with one unit and variable costs per crop unit:

$$d(x, N) = \frac{N}{937.67} \cdot (-0.180x^2 + 6.425x), \tag{6}$$

where x – variable production costs per 1 ha of harvested wheat area, UAH thousand; N – is the planned area of wheat threshing by one combine harvester, ha.

Later, the variable d in the second equation of system (3) was replaced by the right-hand side of expression (6):

$$f_3(x, d) = \begin{cases} (-0.180x^2 + 6.425x) \text{ if } d \leq 10 \\ \left[(1.1 - 0.01\frac{N}{937.67}(-0.180x^2 + 6.425x)\right](-0.180x^2 + 6.425x) \text{ if } d \geq 10 \end{cases}, \tag{7}$$

where, $f_3(x)$ – is the expected yield of wheat, tons/ha; x – variable production costs per 1 ha of harvested wheat area, UAH thousand; d – duration of the collection campaign, days; N – is the planned area of wheat threshing by one combine harvester, h.

A graphic illustration of the dependence of wheat productivity on variable costs at different harvesting areas indicates a reduction in non-productive losses in the case of a reduction in the load on the grain harvester and an increase in the technological efficiency of grain production (figure 1).

The next step was the modeling of the impact on the economic efficiency of grain production of the intensity and load on grain-harvesting equipment during wheat threshing. For this reason, the system of equations (7) was transformed. In particular, based on the assumption of one hundred percent marketability of grain production, in order to determine the expected volume of marketable products, the equations were multiplied by the average price of wheat grain sold by agricultural enterprises of Ukraine in 2020, which, according to the official website of the State Statistics Service, was 386.75 UAH/ha. Taking into account the measurement of variable costs per crop unit in the system of equations (7) in thousand UAH, the price of 1 t of wheat grain was converted into the unit of the same name.

After that, to determine the expected profit, the right-hand side of the equations was reduced by the value of variable costs x and the average value of fixed costs in the production of wheat

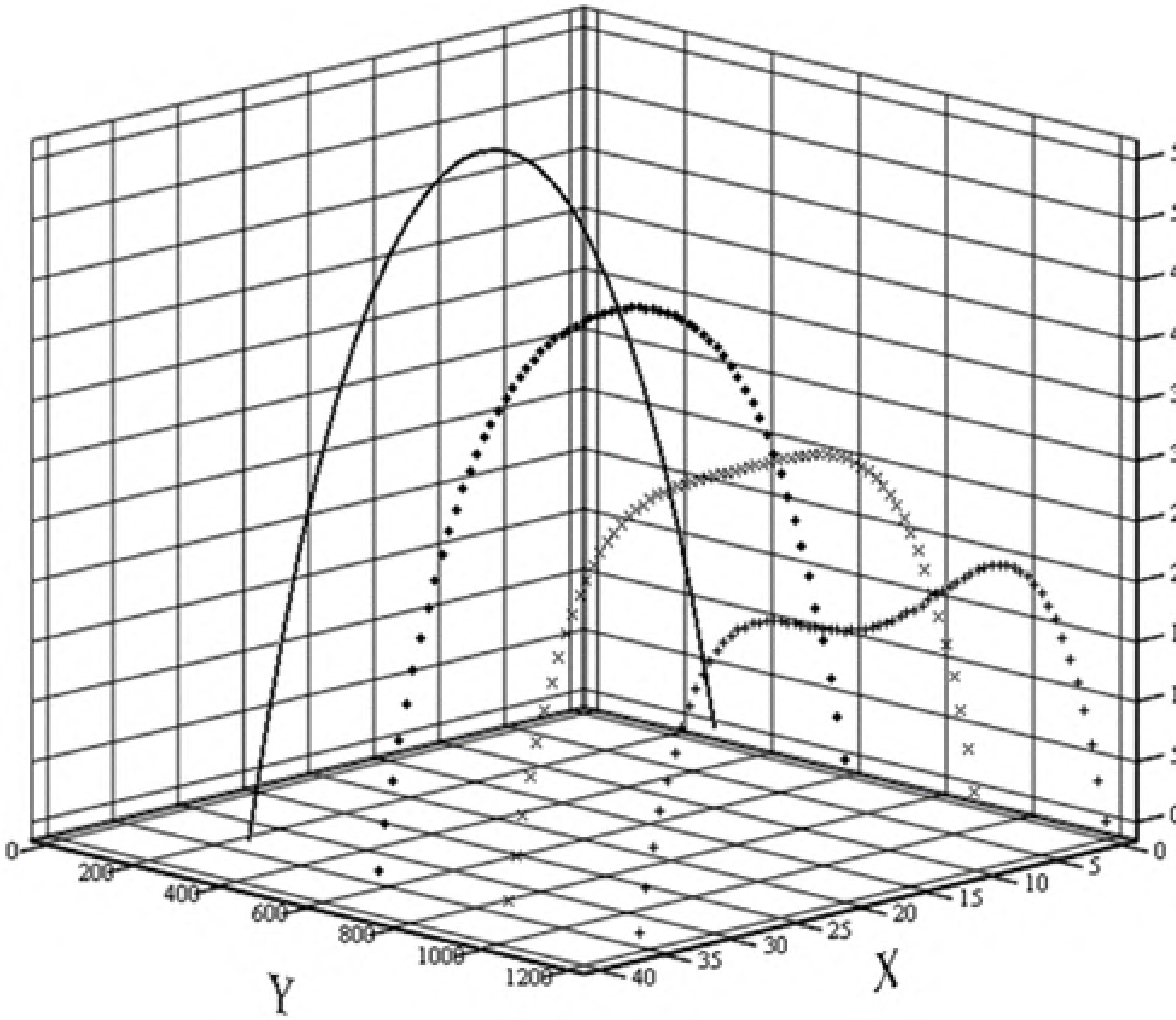

Figure 1. Impact on wheat yield of production intensity and conditions of use of harvesting equipment by agricultural enterprises of Ukraine in 2020 (according to the official website of the State Statistics Service of Ukraine `http://www.ukrstat.gov.ua/`). Graph of dependence of yield (centner per ha) on variable production costs per 1 ha of crops (UAH thousand) at $+++$ – annual load on a grain harvester of 1200 hectares; $\times\times\times$ – annual load on a grain harvester of 900 hectares; $***$ – annual load on a grain harvester of 600 hectares; —— – annual load on a combine harvester of 300 hectares; X – variable production costs per 1 ha of area, UAH thousand; Y – annual load on the grain harvester, ha.

grain, which, according to the analysis of the reporting on the costs of agricultural enterprises of Ukraine for 2020, amounted to 2,711 thousand UAH/ha.

$$f_6(x,d) = \begin{cases} (-0.180x^2 + 6.425x) - x - 2.711 \text{ if } d \leq 10 \\ \left[(1.1 - 0.01 \cdot \frac{N}{937.67}(-0.180x^2 + 6.425x)\right] \cdot (-0.180x^2 + 6.425x) \text{ if } d \geq 10 \end{cases}, \quad (8)$$

where $f_6(x,d)$ – is the expected yield of wheat, tons/ha; x – variable production costs per 1 ha of harvested wheat area, UAH thousand; d – duration of the collection campaign, days; N – is the planned area of wheat threshing by one combine harvester, h.

Graphical interpretation of the behavior of function (8) indicates a decrease in the maximum profit, as well as the optimum cost, which guarantees its achievement in case of an excessive increase in the load on the grain harvester (figure 2).

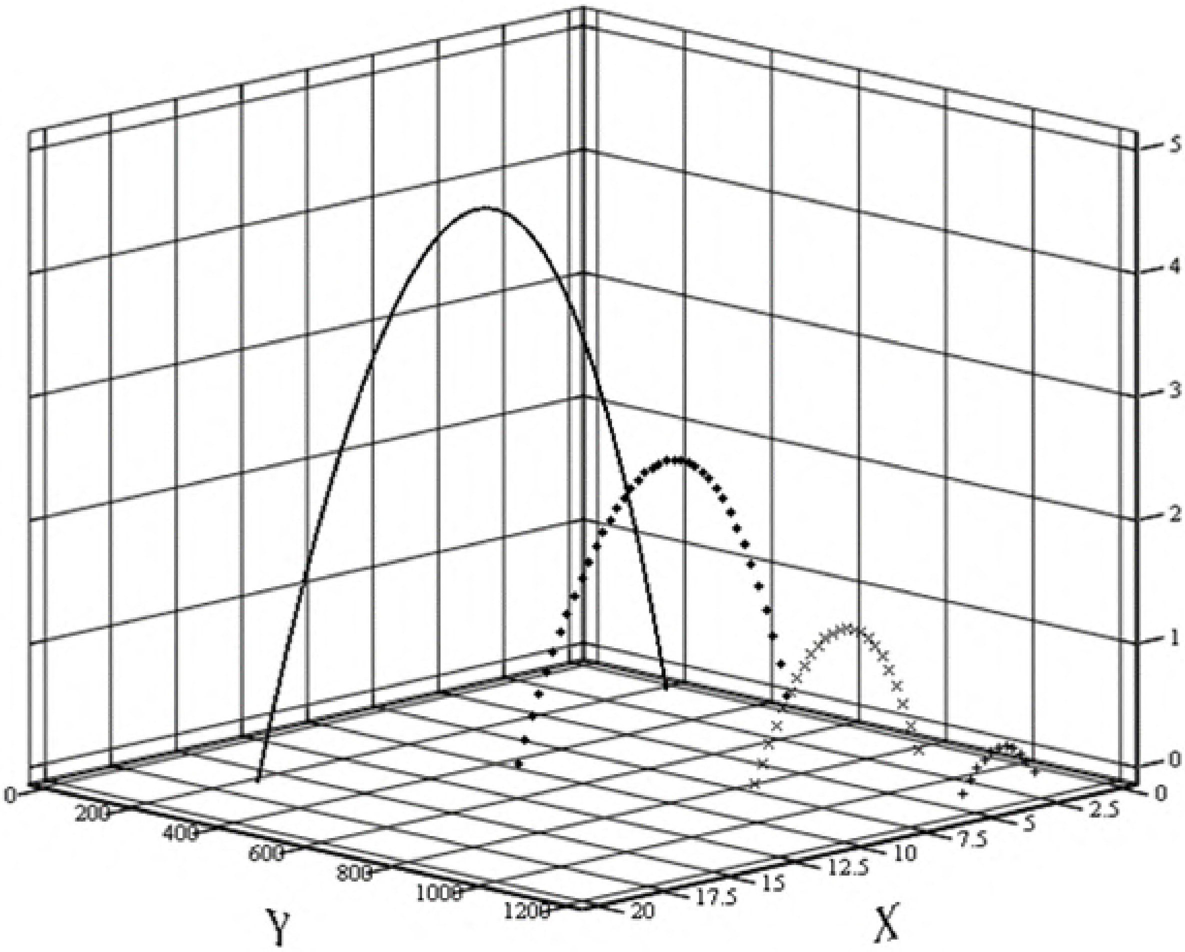

Figure 2. Impact on the economic efficiency of wheat production of production intensity and conditions of use of available harvesting equipment by agricultural enterprises of Ukraine in 2020 (according to the official website of the State Statistics Service of Ukraine `http://www.ukrstat.gov.ua/`). Dependence of profit (thousand hryvnias per ha) on production costs per 1 ha of crops (*UHA thousand*) at + + + – annual load on a grain harvester of 1200 hectares; × × × – annual load on a grain harvester of 900 hectares; ∗ ∗ ∗ – annual load on a grain harvester of 600 hectares; —— – annual load on a combine harvester of 300 hectares; X – variable production costs per 1 ha of area, UAH thousand; Y – annual load on the grain harvester, ha.

So, under the conditions when each harvester of an agricultural enterprise accounts for 300 hectares of wheat crops, the maximum profit of 4.2 thousand UAH/ha is guaranteed by technology with variable costs of 9.0 thousand UAH/ha. Instead, the choice of this technology at a load of 1,200 ha leads to a loss of -2.7 thousand UAH/ha. Under such a load, the technology with variable production costs of 3.9 thousand UAH/ha is optimal, for which the financial result will be equal to +0.4 thousand UAH/ha.

Therefore, under the conditions of threshing 1200 hectares of wheat with each combine harvester, it would be more expedient for the farm to use the technology with variable costs per crop unit almost six times lower compared to the technology that allows to achieve maximum productivity. It is clear that the rejection of industrial technologies reduces the efficiency of using the resource potential of agricultural formations, and therefore it is logical to increase investments in the technical base of harvesting operations. But taking into account the effect of agrobiological factors, the payback of such investments has a declining character. Therefore, when determining the optimal amount of capital and current costs, model (8) was transformed by including the increase in depreciation deductions and other fixed costs due to capital investment.

So, to calculate the increase in depreciation deductions, the average costs for the purchase of a combine harvester in the reporting year – UAH 4,845.4 thousand were evenly distributed over the 12 years recommended by the John Deere company as a guideline for the productive use of this brand of combine harvester. The obtained value – UAH 403.8 thousand should be distributed to the entire fleet of combines and the planned load during wheat harvesting. For example, in the case of doubling the fleet of combines, the average increase for each combine will be 50% of UAH 403.8 thousand, similarly, in the case of a fourfold increase in the fleet, the share of purchased will reach three quarters, and therefore each combine will account for 75% of 403.8 UAH.

Taking this into account, the formula for calculating the increase in depreciation deductions looks like this:

$$A = \frac{403.8 \cdot n}{N}, \tag{9}$$

where n – is the share of newly purchased grain harvesters in their total number; N – annual load on the grain harvester, ha.

In addition, a potential increase in fixed costs was formalized under the conditions of payment of interest for the use of a loan taken out to cover the costs of purchasing a combine harvester. Thus, according to the statistical data of the official website of the National Bank of Ukraine, in 2020, agricultural commodity producers attracted long-term loans for the purchase of equipment at an average rate of 16%. Thus, under the conditions of linear accrual of interest payments, the annual cost of paying interest (I) will be equal to:

$$A = \frac{775.3 \cdot n}{N}, \tag{10}$$

where n – is the share of newly purchased grain harvesters in their total number; N – annual load on the grain harvester, ha.

So, taking into account the potential increase in fixed costs, the system of equations for determining the expected profit looks like this:

$$f_7(x,d) = \begin{cases} (-0.180x^2 + 6.425x) - x - 2.711 \text{ if } d \leq 10 \\ \left[(1.1 - 0.01 \cdot \dfrac{N}{937.67} \cdot (-0.180x^2 + 6.425x)\right] \cdot \\ \cdot(-0.180x^2 + 6.425x) - \dfrac{(403.8 + 775.3) \cdot n}{N} \text{ if } d \geq 10 \end{cases}, \tag{11}$$

where $f_7(x,d)$ – is the expected yield of wheat, tons/ha; x – variable production costs per 1 ha of harvested wheat area, UAH thousand; d – duration of the collection campaign, days; N – is the planned area of wheat threshing by one combine harvester, h.

Graphical interpretation of the behavior of function (11) shows the non-linearity of changes in the payback of investments (figure 3).

In particular, the reduction of the load from 1,200 ha to 900 ha, due to the expansion of the collection equipment park, leads to an increase in fixed costs by 0.3 thousand UAH/ha. As

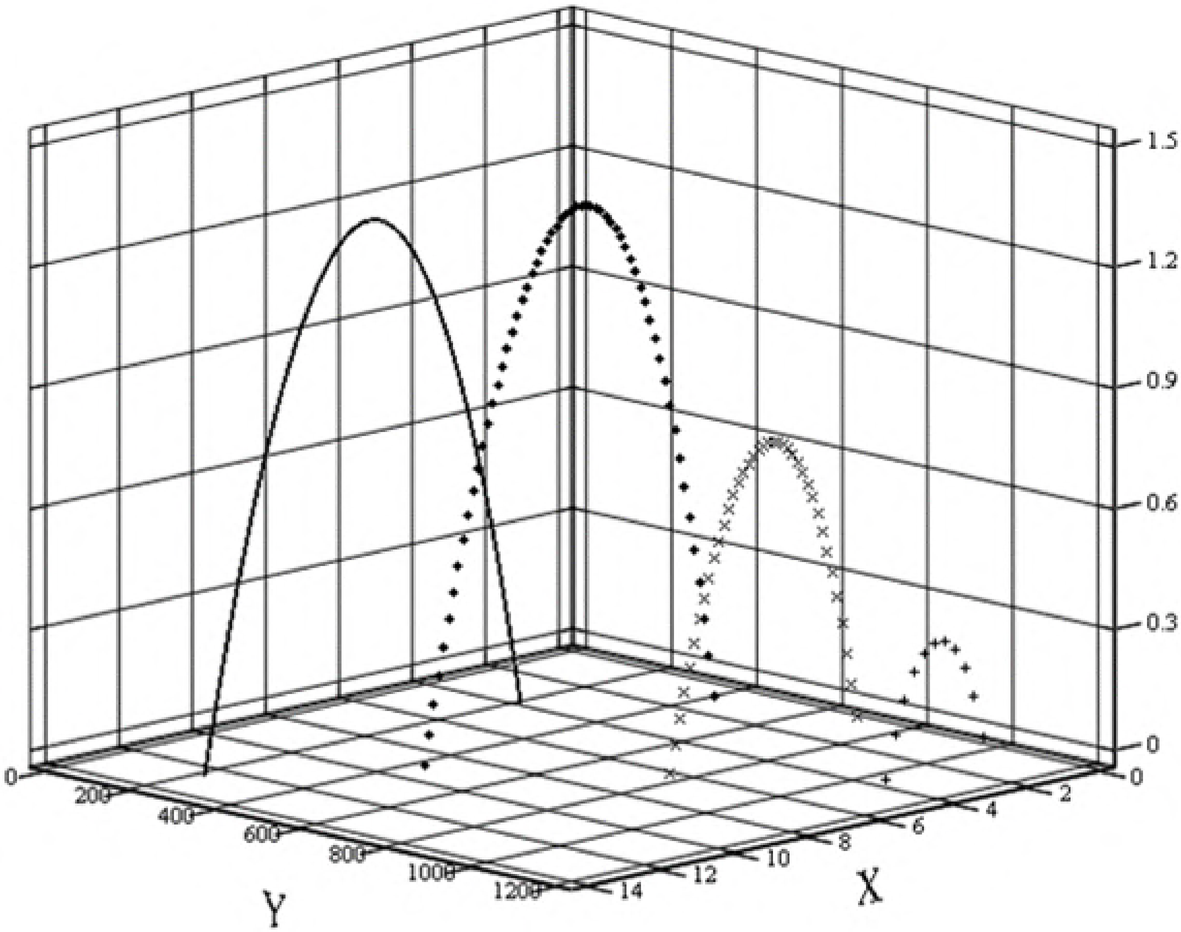

Figure 3. Impact on the economic efficiency of wheat production of production intensity and conditions of use of existing and newly acquired harvesting equipment by agricultural enterprises of Ukraine in 2020 (according to the official website of the State Statistics Service of Ukraine `http://www.ukrstat.gov.ua/`). Graph of dependence of yield (centner per ha) on variable production costs per 1 ha of crops (UAH thousand) at $+++$ – annual load on a grain harvester of 1200 hectares; $\times\times\times$ – annual load on a grain harvester of 900 hectares; $***$ – annual load on a grain harvester of 600 hectares; —— – annual load on a combine harvester of 300 hectares; X – variable production costs per 1 ha of area, UAH thousand; Y – annual load on the grain harvester, ha.

a result, it becomes possible to switch to technology with variable costs of UAH 5,000 with a simultaneous increase in the production intensity indicator by 1,100 UAH/ha (t1). At the same time, the consequence of reducing the duration of the harvesting company and reducing non-productive costs is an increase in productivity to UAH 23.1 thousand, which, with one hundred percent marketability of production, is equivalent to an increase in revenue by 1.9 thousand UAH /ha ($23.1 - 18.3 \times 0.3868$). As a result, the profit of the agricultural enterprise increases by 0.4 thousand UAH/ha. Similarly, under the conditions of reducing the load from 1,200 to 600 ha, the expected profit increase will reach 1,000 UAH/ha. At the same time, under the conditions of reducing the load from 1,200 to 300 hectares, the financial result will increase by only UAH 0.9 thousand, which indicates a decrease in the marginal efficiency of costs.

Thus, in the case of an increase in the park, which allows to reduce the load from 900 to 600

Table 1. The influence of the load on the John Deere S670 combine harvester on the optimal intensity and efficiency of wheat grain production by agricultural enterprises in 2020 (according to the official website of the State Statistics Service of Ukraine `http://www.ukrstat.gov.ua/`).

Indicators	Load on combine harvester, ha			
	300	600	900	1200
Optimum expenses, thousand hryvnias/ha				
plenteous	17.8	17.8	17.8	17.8
profitable	9.0	6.7	5.0	3.9
Productivity (c/ha) with costs at the level				
crop optimum	52.5	42.0	31.4	20.9
profitable optimum	41.7	30.6	23.1	18.3
Financial result (thousand hryvnias/ha) with costs at the level of the harvest optimum, under the conditions of use				
using exclusively available grain harvesters	0.4	-4.5	-8.5	-12.6
investments in the renewal of the fleet of grain harvesters	-1.4	-5.4	-9.5	-12.6
Financial result (thousand hryvnias/ha) with expenses at the level of the profitable optimum, under the conditions of use				
using exclusively available grain harvesters	4.2	2.3	1.1	0.4
investments in the renewal of the fleet of grain harvesters	1.3	1.4	0.8	0.4
Average fixed costs, thousand UAH/ha	2.7	2.7	2.7	2.7
Investments are included in the current year's fixed costs	2.9	1.0	0.3	-
including including depreciation	1.0	0.3	0.1	-
interest expense	1.9	0.6	0.2	-

ha, the increase in fixed costs is 0.7 thousand UAH/ha, the optimal level of variable costs is 1.7 thousand UAH/ha, marketable products – 2.9 thousand UAH/ha $(30.6 - 23.1 \times 0.3868)$. As a result, the marginal return on costs will be equal to +20.8% $((2.9-(0.7+1.7))/(0.7+1.7)\times 100)$. On the other hand, in the event of a decrease in the load from 600 to 300 ha, fixed and variable costs, as well as marketable products, increase by 2.3, 1.9 and 2.9 thousand UAH/ha, respectively, and the marginal loss of costs is -30.9% . Therefore, under unchanged conditions (production technology, product price situation, production resources, agricultural machinery, interest rates, etc.), the mark of 600 hectares of wheat crops per John Deere S670 combine harvester is the economic limit of the feasibility of investments in the renovation of the combine harvester park of domestic agricultural enterprises by purchasing similar or similar units.

3. Conclusions and prospects for further research

The implementation of sustainable development goals for Ukraine determines the intensification of processes in the domestic agricultural sector, brings to the fore the problems of ensuring food security of the state, increasing the production of safe products while preserving landscapes and minimizing anthropogenic pressure. In turn, the seizure of part of the territory, contamination of the liberated and adjacent territories with explosive objects further actualize the problem of rational use of land resources. Under such conditions, only further introduction of innovations aimed at increasing yields and the use of intensive technologies is perhaps the only possible way to develop domestic agriculture. The latter places strict requirements on the technical condition of its resource potential. Unfortunately, the unsatisfactory technical condition of the grain harvesting machinery fleet and its destruction as a result of hostilities exacerbate the problem of technical support for grain production, in particular for harvesting. Under such conditions, an important task is to develop methodological techniques for determining the optimal, harmonized values of investments in the reproduction of resource potential and operating costs.

The tested methodological approach allows determining the optimal level of investment in the renovation of the combine harvester fleet, taking into account the peculiarities of wheat production organization, grain price conditions, material resources, harvesting equipment, and financial factors. The calculations showed that it is economically inexpedient to invest in the renewal of the combine harvester fleet with John Deere S670 or similar combine harvesters if one unit has less than 600 hectares of wheat crops. A positive feature of the tested approach is the ability to minimize unproductive costs by taking into account technological and market factors in determining the optimal level of costs. Instead, the introduction of innovations leads to a change in the form of the production function, which should affect the dynamics of the marginal efficiency of investments, and therefore it is promising to expand approaches to modeling and take into account the role of innovations in finding the optimal level of current costs and investments.

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References

[1] Łuczka W, Kalinowski S and Shmygol N 2021 *Energies* **14**(14) 4208 URL https://doi.org/10.3390/en14144208
[2] FAO 2022 *FAO Strategy on Climate Change 2022–2031* (Rome: Food and Agriculture Organization of the United Nations) URL https://www.fao.org/3/cc2274en/cc2274en.pdf
[3] Griggs D, Stafford Smith M, Rockström J, Öhman M C, Gaffney O, Glaser G and Shyamsundar P 2014 *Ecology and Society* **19**(4) 49 URL https://doi.org/10.5751/ES-07082-190449
[4] Foley J 2007 *Science* **356**(6335) 251–252 URL https://doi.org/10.1126/science.aal4863
[5] Rockström J, Steffen W, Noone K, Persson Å, Chapin, III F S, Lambin E, Lenton T M, Scheffer M, Folke C, Schellnhuber H J, Nykvist B, de Wit C A, Hughes T, van der Leeuw S, Rodhe H, Sörlin S, Snyder P K, Costanza R, Svedin U, Falkenmark M, Karlberg L, Corell R W, Fabry V J, Hansen J, Walker B, Liverman D, Richardson K, Crutzen P and Foley J 2009 *Ecology and Society* **14**(2) 32 URL https://doi.org/10.5751/ES-03180-140232
[6] Steffen W, Richardson K, Rockström J, Cornell S E, Fetzer I, Bennett E M, Biggs R, Carpenter S R, de Vries W, de Wit C A, Folke C, Gerten D, Heinke J, Mace G M, Persson L M, Ramanathan V, Reyers B and Sörlin S 2015 *Science* **347**(6223) 1259855 URL https://doi.org/10.1126/science.1259855
[7] Hummels H and Argyrou A 2021 *Journal of Cleaner Production* **278** 123804 URL https://doi.org/10.1016/j.jclepro.2020.123804
[8] Byrch C, Milne M J, Morgan R and Kearins K 2015 *Accounting, Auditing & Accountability Journal* **28**(5) 671–705 URL https://doi.org/10.1108/aaaj-08-2013-1438
[9] Larsen G L 2008 An Inquiry Into the Theoretical Basis of Sustainability: Ten Propositions *Understanding the Social Dimension of Sustainability* ed Dillard J, Dujon V and King M C (New York: Routledge) pp 45–82
[10] Hopwood B, Mellor M and O'Brien G 2005 *Sustainable Development* **13**(1) 38–52 URL https://doi.org/10.1002/sd.244
[11] Porter J R, Challinor A J, Henriksen C B, Howden S M, Martre P and Smith P 2019 *Global Change Biology* **25**(8) 2518–2529 URL https://doi.org/10.1111/gcb.14700
[12] von Braun J, Gulati A and Kharas H 2017 *Economics: The Open-Access, Open-Assessment E-Journal* **11**(2017-32) 1–13 URL https://doi.org/10.5018/economics-ejournal.ja.2017-32

[13] Pardey P G, Chan-Kang C, Dehmer S P and Beddow J M 2016 *Nature* **537**(7620) 301–303 ISSN 1476-4687 URL https://doi.org/10.1038/537301a
[14] Ackerberg D, Caves K and Frazer G 2015 *Econometrica* **83**(6) 2411–2451 URL https://doi.org/10.14254/2071-789X.2022/15-2/19
[15] Blundell R and Bond S 2000 *Econometric Reviews* **19**(3) 321–340 URL https://doi.org/10.1080/07474930008800475
[16] Demirer M 2022 Production function estimation with factor-augmenting technology: An application to markups URL https://demirermert.github.io/Papers/Demirer_production_function%202.pdf
[17] Gandhi A, Navarro S and Rivers D A 2020 *Journal of Political Economy* **128**(8) 2973–3016 URL https://doi.org/10.1086/707736
[18] Levinsohn J and Petrin A 2003 *The Review of Economic Studies* **70**(2) 317–341 ISSN 0034-6527 URL https://doi.org/10.1111/1467-937X.00246
[19] Olley G S and Pakes A 1996 *Econometrica* **64**(6) 1263–1297 ISSN 00129682, 14680262 URL http://www.jstor.org/stable/2171831
[20] De Loecker J and Syverson C 2021 Chapter 3 - An industrial organization perspective on productivity *Handbook of Industrial Organization, Volume 4* (*Handbook of Industrial Organization* no 1) ed Ho K, Hortaçsu A and Lizzeri A (Elsevier) pp 141–223 URL https://doi.org/10.1016/bs.hesind.2021.11.003
[21] Amiti M and Konings J 2007 *American Economic Review* **97**(5) 1611–1638 URL https://doi.org/10.1257/aer.97.5.1611
[22] Bloom N, Draca M and Van Reenen J 2015 *The Review of Economic Studies* **83**(1) 87–117 ISSN 0034-6527 URL https://doi.org/10.1093/restud/rdv039
[23] Brandt L, Van Biesebroeck J, Wang L and Zhang Y 2017 *American Economic Review* **107**(9) 2784–2820 URL https://doi.org/10.1257/aer.20121266
[24] Keller W and Yeaple S R 2009 *The Review of Economics and Statistics* **91**(4) 821–831 ISSN 0034-6535 URL https://doi.org/10.1162/rest.91.4.821
[25] Halpern L, Koren M and Szeidl A 2015 *American Economic Review* **105**(12) 3660–3703 URL https://doi.org/10.1257/aer.20150443
[26] Syverson C 2011 *Journal of Economic Literature* **49**(2) 326–65 URL https://doi.org/10.1257/jel.49.2.326
[27] De Loecker J and Warzynski F 2012 *American Economic Review* **102**(6) 2437–71 URL https://doi.org/10.1257/aer.102.6.2437
[28] De Loecker J, Eeckhout J and Unger G 2020 *The Quarterly Journal of Economics* **135**(2) 561–644 ISSN 0033-5533 URL https://doi.org/10.1093/qje/qjz041
[29] De Loecker J 2011 *Econometrica* **79**(5) 1407–1451 URL https://doi.org/10.3982/ECTA7617
[30] De Loecker J, Goldberg P K, Khandelwal A K and Pavcnik N 2016 *Econometrica* **84**(2) 445–510 URL https://doi.org/10.3982/ECTA11042
[31] Dhyne E, Petrin A, Smeets V and Warzynski F 2022 Theory for Extending Single-Product Production Function Estimation to Multi-Product Settings Working Paper 30784 National Bureau of Economic Research URL https://doi.org/10.3386/w30784
[32] De Loecker J and Goldberg P K 2014 *Annual Review of Economics* **6**(1) 201–227 URL https://doi.org/10.1146/annurev-economics-080113-104741
[33] Orr S 2022 *Journal of Political Economy* **130**(11) 2771–2828 URL https://doi.org/10.1086/720465
[34] Hall R E 1989 Invariance Properties of Solow's Productivity Residual Working Paper 3034 National Bureau of Economic Research URL https://doi.org/10.3386/w3034
[35] Basu S and Fernald J 1997 *Journal of Political Economy* **105**(2) 249–283 URL https://doi.org/10.1086/262073
[36] Sawhney M, Wolcott R C and Arroniz I 2006 *MIT Sloan Management* **47** 74–81 URL https://hbsp.harvard.edu/product/SMR207-PDF-ENG
[37] Du S, Bhattacharya C B and Sen S 2011 *Management Science* **57**(9) 1528–1545 URL https://doi.org/10.1287/mnsc.1110.1403
[38] Flammer C 2015 *Management Science* **61**(11) 2549–2568 URL https://doi.org/10.1287/mnsc.2014.2038
[39] Miller D J, Fern M J and Cardinal L B 2007 *The Academy of Management Journal* **50**(2) 308–326 ISSN 00014273 URL http://www.jstor.org/stable/20159856
[40] Wadhwa A and Kotha S 2006 *Academy of Management Journal* **49**(4) 819–835 URL https://doi.org/10.5465/amj.2006.22083132
[41] Ionescu G, Firoiu D, Pîrvu R, Enescu M, Rădoi M I and Cojocaru T 2020 *Sustainability* **12**(18) 7250 URL https://doi.org/10.3390/su12187250
[42] Iqbal N, Khan A, Gill A S and Abbas Q 2020 *Environmental Science and Pollution Research* **27**(29) 36242–36253 ISSN 1614-7499 URL https://doi.org/10.1007/s11356-020-09642-y

[43] Muñoz P and Cohen B 2018 *Business Strategy and the Environment* **27**(3) 300–322 URL https://doi.org/10.1002/bse.2000
[44] Dean T J and McMullen J S 2007 *Journal of Business Venturing* **22**(1) 50–76 URL https://doi.org/10.1016/j.jbusvent.2005.09.003
[45] Gigauri I and Bogacz-Wojtanowska E 2022 *Economics and Sociology* **15**(2) 312–334 URL https://doi.org/10.14254/2071-789X.2022/15-2/19
[46] Gigauri I 2022 *International Journal of Sustainable Entrepreneurship and Corporate Social Responsibility* **7**(1) 1–17 URL http://doi.org/10.4018/IJSECSR.304897
[47] Oliynyk O V and Makohon V V 2021 *Visnyk KHNAU. Ekonomichni nauky* **1** 207–221
[48] Kyrychenko V V, Popov S I, Kobyzyeva L N, Balyuk S A *et al.* 2015 *Peculiarities of harvesting early cereals and legumes in farms of Kharkiv region in 2015* (Kharkiv: KhNTUSG)
[49] Kravchuk V I and Mel'nyk Y F 2009 *Machines for harvesting grain and industrial crops* (Doslidnyts'ke: UkrNDIPVT im. L. Pohoriloho)
[50] Ruzhyts'kyy M A, Ryabets' V I, Kiyashko V M, Burlaka V M and Ivashyna M B 2011 *Operation of machinery and equipment* (Kyiv: Ahroosvita)
[51] Vitvits'kyy V V, Muzyka P M, Kyslyachenko M F and V L I 2010 *Standards for the cost of living and tangible labor for the production of cereals* (Kyiv: NDI Ukrahropromproduktyvnist')
[52] Province of Manitoba 2023 agriculture - Cost Of Production Guides & Calculators URL https://www.gov.mb.ca/agriculture/farm-management/production-economics/cost-of-production.html
[53] Tractorhousecom 2023 Harvest Equipment For Sale URL https://www.tractorhouse.com/listings/for-sale/harvest-equipment/1102

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Model aspect of the study of the processes of sustainable development of socio-economic systems

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Abstract. The triune concept of sustainable development takes into account environmental, social and economic issues in general. At the same time, the solution of the problems of resource conservation and socio-economic development do not contradict each other, but contribute to mutual reinforcement. The purpose of this study is to build, describe, test and analyze economic and mathematical models of the processes of self-organization of the socio-economic system within the framework of the concept of sustainable development. The considered models take into account both quantitative and qualitative characteristics. The research methodology is based on the assumption that the system under consideration is dynamic. The study makes it possible to evaluate the process of sustainable development of the socio-economic system in terms of the formation and influence of its characteristics on the overall result. Various options for formalizing the level of motivation of economic activity are described and analyzed, one of which is based on the economic interpretation of the Weber-Fechner psychophysiological law. The assumption of the continuous development of innovative technologies made it possible to reveal the existence of a "fatigue point", the onset of which indicates the possibility of increasing the growth rate of production activities due to its technological transformation.

1. Introduction

Human development in recent decades is often characterized by growth adverse impact on the external environment. Factors in this are also wars, political and socio-economic instability. People's actions have a negative impact on the environment. This threatens the survival of the Earth and future generations. This necessitates changes aimed at more rational and effective management of resources, which will reduce pressure and negative impact on the environment.

As a result, it became necessary to develop strategies for the development of mankind that would prevent the deterioration of the quality of the environment, eliminate the consequences of such deterioration, and contribute to the formation of conditions for providing resources for the current and future generations [1].

Such a viable behavior, to ensure the long-term exploitation of resources, without putting a threat to future generations, is considered within the framework of the concept of sustainable development [2].

The most progressive concept is the triune concept of sustainable development: environmental, social and economic issues are considered as a whole, and the goals of resource conservation and socio-economic development contribute to mutual reinforcement [3].

This understanding of sustainable development implies a balance between the three components of sustainability [2]:

- environmental sustainability, which is aimed at maintaining the quality of the environment necessary for the implementation of economic activities and ensuring the quality of life of people;
- social sustainability that seeks to ensure human rights and equality, the preservation of cultural identity, respect for cultural diversity, race and religion;
- economic sustainability needed to maintain natural, social and human capital to ensure living standards.

Only such an interpretation of sustainable development makes it possible to form the conditions for achieving a high standard of living, a developed economy and conservation of resources.

This approach is consistent with the definition of Brundtland [4], who defined sustainable development as the process of meeting the needs of the subject in the current cycle without harming the ability to meet the needs in the next cycle.

This concept assumes that the effective solution of environmental problems should be accompanied by the development of environmental awareness in the performance of economic entities of their main functions, the use of appropriate forms of economic behavior [1].

Thus, it is relevant to study the forms of economic behavior in the context of sustainable development and develop methods for quantitative and qualitative assessment of the results of their use.

At the same time, the current stage of development of the concept of sustainable development is characterized by the transfer of the problem from the global and macroeconomic levels to the microeconomic level, the subjects of which are actively involved in causing harm to the environment and become subjects of its elimination [5].

With this approach, the sustainability of an individual microeconomic entity becomes not just a concept, but also an object of sustainable development, which forms the features of modeling, design, organization and management [6].

Thus, in the article [7], the problems of decision-making in the management systems for sustainable development of complex technological and socio-economic objects are studied, the limitations of traditional expert systems are shown.

The study [8] developed a methodological approach for conducting a comprehensive assessment of the socio-economic parameters of sustainable development. To obtain justified results, the work uses such modeling methods as a fuzzy logical model, the Saaty hierarchy method, the Mamdani algorithm, quantitative and qualitative methods of comparison.

In the article [9], the logistics system of enterprise management is presented in the form of an optimization model that combines economic and environmental factors. This model allows you to evaluate and take into account the impact on the environment.

Article [10] is devoted to the study of a dynamic model for the optimal use of water resources with taking into account the interests of regional counterparties of the two hierarchy levels. The problem is solved by simulation methods.

At the same time, the management of sustainable development processes often provides for such a type as organization by structures of the upper hierarchical level [8, 10–12].

The purpose of the study is to substantiate the strategies of economic behavior of socio-economic entities within the framework of the concept of sustainable development. To achieve this goal, it is necessary to complete the following tasks: within the framework of existing methods of economic and mathematical modeling, describe an adaptive process model that takes into account the self-organizational and reflexive features of a socio-economic subject;

conduct model experiments to identify cause-and-effect relationships between the motives for the formation of economic behavior and results.

2. Results

It should be agreed that in socio-economic systems, the main system-forming element of models is meaningful or semantic approaches, and more complete models are built on target settings, which are based on value orientations, which are the main, fundamental basis for choosing system management models [13]. Most of these systems are dynamic.

The two fundamental elements of the concept of sustainable development are development and sustainability. At the same time, classical economic theory considers development within the framework of economic growth [2].

In the study [14], an isomorphic connection between the concept of "dynamic system" and "autonomous system of ordinary differential equations" is established. The main mathematical apparatus in this case is the qualitative theory of differential equations [15], and the model is formalized by a system of autonomous differential equations

$$\frac{\mathrm{dx}_i}{\mathrm{dt}}=\mathrm{F}_i\left(\mathrm{x}_1,\mathrm{x}_2,..,\mathrm{x}_n\right),(i=1,2,..,n), \tag{1}$$

where x_i is some quantitative characteristic of the socio-economic agent, which takes part in the process, which corresponds to the coordinate of the vector in the n-dimensional economic space.

The approach to building a possible full-factor model of the process of sustainable development consists in the balanced consideration of economic, social and environmental factors, among which the following are distinguished: individual; intrasystemic; external. At the same time, the external influence can be characterized by a known function or have a random nature.

In this case, system (1) takes the form

$$\frac{\mathrm{dx}_i}{\mathrm{dt}}=\mathrm{F}_i\left(\mathrm{x}_1,\mathrm{x}_2,..,\mathrm{x}_n,t\right),(i=1,2,..,n) \tag{2}$$

and is classified as a system of ordinary differential equations.

The two fundamental elements of the concept of sustainable development are development and sustainability. At the same time, classical economic theory considers development within the framework of economic growth [2].

If one characteristic is taken as an indicator of the level of development, then in equations (1), (2) $n = 1$. In this case, the development model (growth, increase, accumulation) can be represented in the form

$$\frac{\mathrm{dx}}{\mathrm{dt}}=k\mathrm{x}, \tag{3}$$

where k is a coefficient that characterizes the growth rate.

Equation (3) corresponds to the Malthusian or exponential law of population growth [16]. A particular solution to equation (3) is described by the function

$$\mathrm{x}\left(t\right)=x_0\exp\left(kt\right), \tag{4}$$

where x_0 is the value of the indicator under study at the initial time $t = 0$.

It is obvious that function (4) will correspond to development only when it increases. This is ensured by the condition $k > 0$, the fulfillment of which is accompanied by the theoretical possibility of an infinite increase in the indicator studied in the model

$$\lim_{t\to\infty,k>0} x_0\exp\left(kt\right)=\infty. \tag{5}$$

In this case, the management of the development process in the context of the concept of sustainable development can be accompanied by an organizational impact on the system, which is displayed in equation (3) by the transition $k = k(t)$. That is

$$\frac{\mathrm{dx}}{\mathrm{dt}}=k\left(t\right)\mathrm{x}. \tag{6}$$

It should be noted that some studies suggest modifications to model (3) [17, 18], which allow correcting the dynamics of unlimited growth as a consequence of a lack of resources [19]. At the same time, the limited resources are displayed in such models only indirectly, and the social and environmental components of the concept of sustainable development are absent.

Unlike classical and neoclassical economics, institutional economics provides for bounded rationality [20]. For institutional economics, a characteristic type of management is self-organization [21] and a synergistic approach to management [22]. Equilibrium in this case becomes the main goal of the functioning of the economic entity, which is consistent with the concept of sustainable development.

This principle corresponds to the form of the function $k(t)$ in equation (6)

$$k\left(t\right)=k_{max}\left(1-\frac{\mathrm{x}}{\mathrm{x_{Lim}}}\right), \tag{7}$$

where k_{max} is a constant positive coefficient characterizing the maximum value of the growth rate; x_{Lim} is the value of the indicator under study, limiting its increase.

In this case, equation (6) is transformed to the form

$$\frac{\mathrm{dx}}{\mathrm{dt}}=k_{max}\mathrm{x}\left(1-\frac{\mathrm{x}}{\mathrm{x_{Lim}}}\right), \tag{8}$$

which is a logistic (Verhulst-Pearl) model [23].

The essence of the presented equation is that changes in the system depend on factors that contribute to its development (growth) and factors that inhibit (limit) this development (growth). This means that within the system there is a certain regulatory mechanism that ensures the process of sustainable development at the level of self-organization.

The different influence of individual factors on the overall result is more clearly displayed if equation (8) is converted to the form

$$\frac{\mathrm{dx}}{\mathrm{dt}}=k_{max}\mathrm{x}-\frac{k_{max}}{\mathrm{x_{Lim}}}\mathrm{x}^2. \tag{9}$$

The Verhulst-Pearl equation (8) is quite universal and can be used to describe various dynamic processes [10, 23–26].

Thus, in population models, as the x_{Lim} value, which limits growth, an objective indicator of the capacity of the ecological environment is considered [23, 24], and in models of production processes, in addition to environmental restrictions [10], the consumption potential in the market can be assessed [25].

At the same time, the concept of sustainable development of such socio-economic entities as households also implies a self-organizational type of management of their economic behavior. In this case, a unitary strategy of economic behavior may be characterized by the desire to achieve a level of opportunity x_{Lim} (income) that allows them to satisfy economic needs that correspond to their social and cultural level [26]. This approach to modeling rational economic behavior is consistent with the theory of Gossen [27], according to which rationality is determined by the desire to increase satisfaction (reduce dissatisfaction).

It should be noted that under the initial conditions $x(t_0) = x_0$, a particular solution to equation (8) will be the logistic function

$$x(t) = x_{Lim} \frac{x_0 \exp(k_{max} t)}{x_{Lim} + x_0 (\exp(k_{max} t) - 1)}, \tag{10}$$

for which

$$\lim_{t \to \infty} x(t) = x_{Lim}. \tag{11}$$

Thus, the dynamics of the results of production activities for given model values of parameters and initial conditions is shown in figure 1.

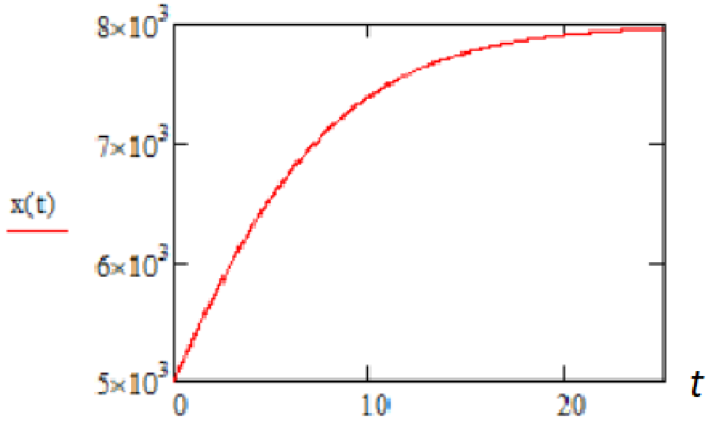

Figure 1. Graph of function (10) at $k_{max} = 0.2$ (productivity growth coefficient); $x_{Lim} = 8000$ pcs (maximum permissible productivity in terms of environmental safety); $x_0 = 5000$ pcs (productivity at the initial moment of time).

By controlling the parameters of the model, one can contribute to the formation of conditions for sustainable development.

A more general case is when the limiting parameter x_{Lim} changes with time, that is, $x_{Lim} = x_{Lim}(t)$. This situation may be a consequence of the development of technologies that allow gradually increasing the effectiveness of economic activity without increasing environmental damage and without increasing the ecological footprint. [28, 29]. We will use the assumption that there is a direct relationship between the innovative level of technology and the level of production acceptable from the point of view of environmental safety.

With the same increase in each period of time, a constant growth rate is observed, and the function itself $x_{Lim} = x_{Lim}(t)$ has the form

$$x_{Lim}(t) = x^0_{Lim} (1 + a_1 t), \tag{12}$$

where x^0_{Lim} is the initial value of x_{Lim}; a_1 is the percentage of growth per unit of time.

If development occurs at a constant rate, but relative to the level reached in the previous time interval, then the function has the form

$$x_{Lim}(t) = x^0_{Lim} (1 + a_2)^t, \tag{13}$$

where a_2 is the percentage of growth per unit of time.

It should be noted that formulas (12), (13) imply discrete time. At the same time, function (13) more correctly reflects the process of sequential development.

Passing to the continuous growth form, function (13) is transformed to the form

$$x_{Lim}(t) = x^0_{Lim} \exp(a_2 t). \tag{14}$$

Using function (14) we transform equation (8)

$$\frac{\mathrm{dx}}{\mathrm{dt}} = k_{max}\mathrm{x}\left(1 - \frac{\mathrm{x}}{x^0_{Lim}\exp(a_2 t)}\right). \tag{15}$$

The general solution of equation (15) has the form

$$x(t) = \frac{x^0_{Lim} x_0 (k_{max} - a_2)}{k_{max}\exp((k_{max} - a_2)t) + x_0}\exp(k_{max} t). \tag{16}$$

The joint dynamics of the results of production activity (16) and function (14) for given model values of parameters and initial conditions is shown in figure 2.

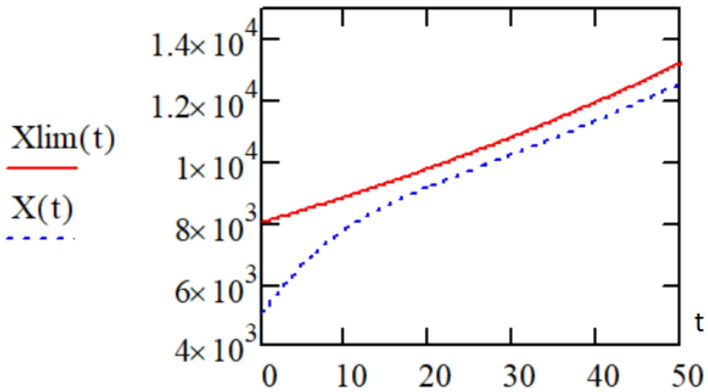

Figure 2. Graphs of functions (14), (16) at $k_{max} = 0,2$ (productivity growth rate); $x^0_{Lim} = 800$ pcs (initial value of maximum allowable capacity); $x_0 = 5000$ pcs (performance at the initial moment of time); $a_2 = 0.01$.

Functions (14), (16) have the equality

$$\lim_{t\to\infty} x(t) = \lim_{t\to\infty} x_{Lim}(t). \tag{17}$$

That is, an increase in the allowable production threshold is accompanied by a corresponding increase in production (figure 2). At the same time, at each moment of time there is some lag, which can be estimated by the function

$$F(t) = x_{Lim}(t) - x(t) = x^0_{Lim}\exp(a_2 t) - \frac{x^0_{Lim} x_0 (k_{max} - a_2)}{k_{max}\exp((k_{max} - a_2)t) + x_0}\exp(k_{max} t). \tag{18}$$

This function characterizes at each moment of time the value of the deviation of the real results of economic activity $x(t)$ from the possible ones $x_{Lim}(t)$. It is not difficult to show that function (18) has an extremum, namely, a minimum. The visualization of this fact is shown in figure 3.

We propose to call the minimum point of function (18) the "fatigue point", which is characterized by the fact that at this point in time the growth of economic activity in a given mode ceases to have a critical impact on its potential development. This can be explained by the

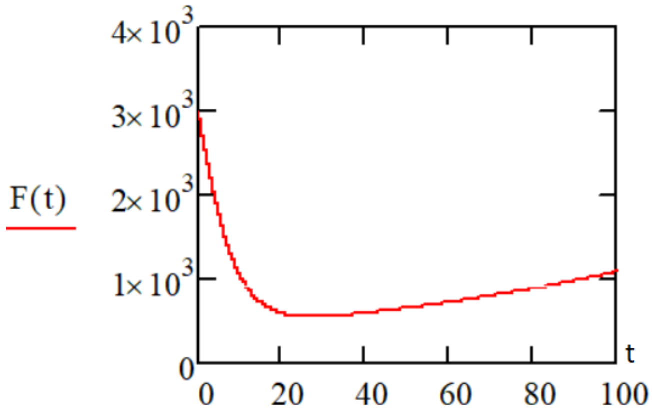

Figure 3. Graphs of functions (8) at $k_{max} = 0,2$ (productivity growth rate); $x^0_{Lim} = 800$ pcs (initial value of maximum allowable capacity); $x_0 = 5000$ pcs (performance at the initial moment of time); $a_2 = 0.01$.

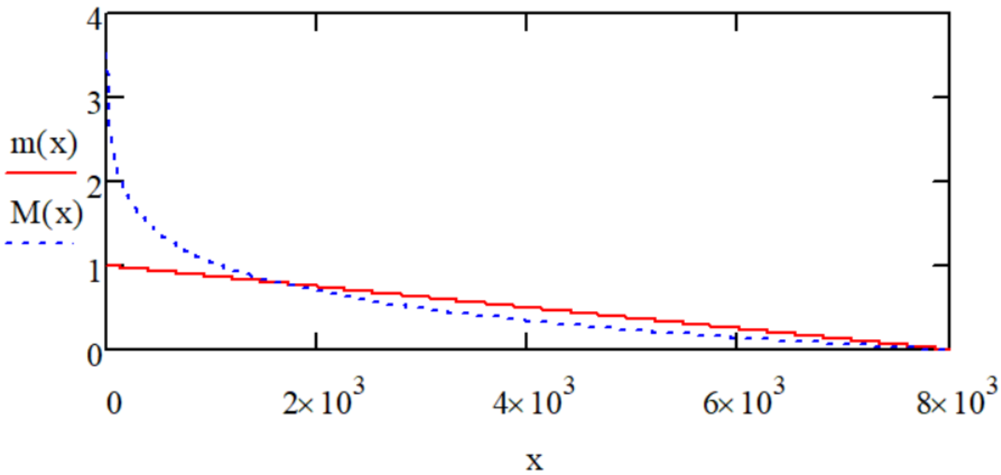

Figure 4. Change in motivation (19) and (20) with $x_{Lim} = 8000$ pcs, $r = 0.5$.

fact that in the situation under study, innovative development concerns only the environmental (resource) component, while the production component remains constant $k_{max} = Const$. This makes it possible to determine the point in time when it becomes possible to increase the growth rate of production activities due to its technological transformation.

Speaking about the self-organization of the processes of sustainable development of socio-economic systems, it should be noted that consciously or subconsciously their motivators may depend on individual or unitary social, cognitive and emotional factors [30].

The level of motivation for the development of the system under the existing constraints x_{Lim} in model (8) is represented by the function

$$m(x) = \left(1 - \frac{x}{x_{Lim}}\right). \tag{19}$$

At the same time, psychological and social factors can influence the assessment of objective quantitative indicators and subjective qualitative indicators. This allows us to give an economic interpretation of the Weber-Fechner psychophysiological law [31] and quantify motivation by the function

$$M\left(x\right)=r\ln\left(\frac{\mathrm{x_{Lim}}}{\mathrm{x}}\right), \tag{20}$$

where r is the scale factor.

Analysis of changes in functions (19), (20) (figure 4) displays their distinctive features.

First, $m(N) \in [0;1]$, and $M(N) \in (0;+\infty)$. Secondly, with a sufficiently large deviation of the values of the indicator of the level of economic activity from the boundary value x_{Lim}, the non-linear motivation function $M(x)$ significantly exceeds the values of $m(x)$, and with small deviations it can become smaller. This fact can be explained by the existence of features of a particular socio-economic system, which, in a critical situation, stimulate the search for additional opportunities to realize the existing potential. Such features are displayed by the scale factor r.

Taking into account the content and form of function (20), equation (8) can be modified

$$\frac{\mathrm{dx}}{\mathrm{dt}}=k_{max}\mathrm{x}r\ln\left(\frac{\mathrm{x_{Lim}}}{\mathrm{x}}\right). \tag{21}$$

The general solution of equation (21) has the form

$$x\left(t\right)=x_{Lim}\exp\left(-ln\left(\frac{\mathrm{x_{Lim}}}{\mathrm{x}}\right)\exp(-k_{max}rt)\right). \tag{22}$$

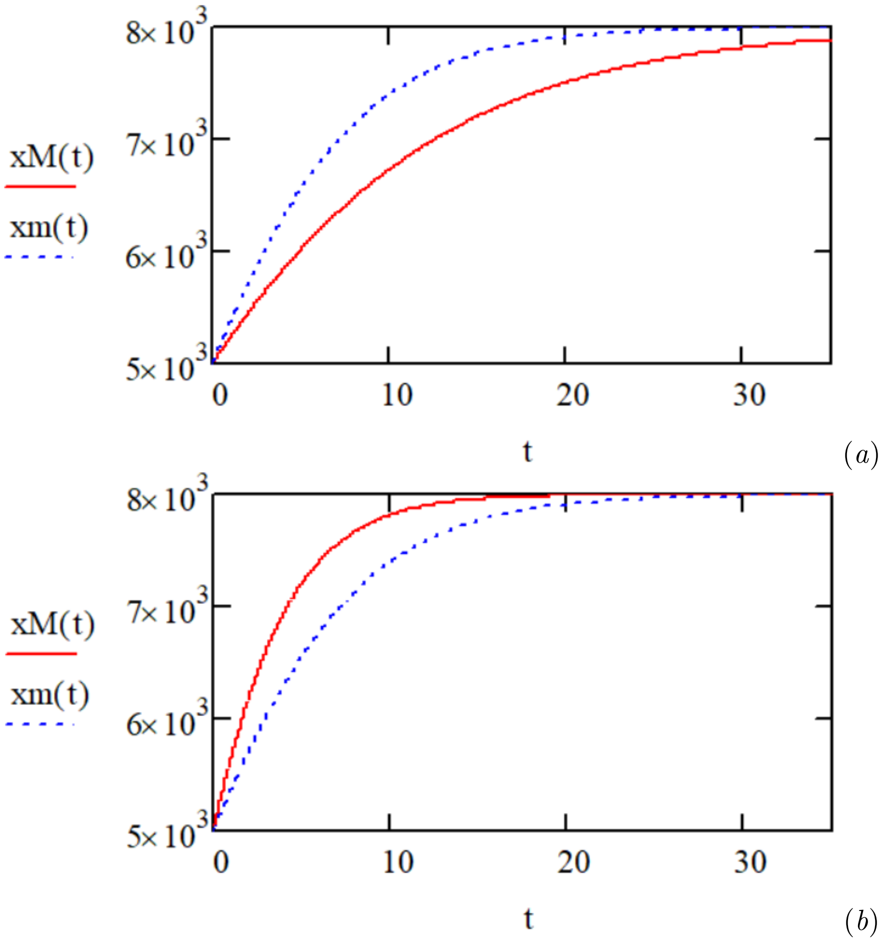

Figure 5. Comparative dynamics of function (10) – $xm(t)$ and function (22) – $xM(t)$ at $x_{Lim} = 8000$ pcs, $x_0 = 5000$ pcs, $k = 0.2$: at $r = 0.5$ (a); at $r = 1.5$ (b).

Let's compare functions (10) and (22) (figure 5).

Obviously, depending on the individual characteristics of the socio-economic system, which are displayed in the model (21) by the scale factor r, the process of sustainable development can proceed less (figure 5a) or more (figure 5b) intensively.

It should also be noted that the use of the previously considered option $x_{Lim} = x_{Lim}(t)$ (14) in model (21) also makes it possible to identify the "fatigue point". The results obtained can be explained by the presence of institutional features of socio-economic systems.

3. Conclusions

1. The proposed methodology for modeling the processes of sustainable development of socio-economic systems is based on a combination of neoclassical and institutional approaches and is characterized by limited rationality, which implies the achievement (maintenance) of an equilibrium state of the socio-economic system.
2. The motivational and stimulating factor in the formation of sustainable development processes is the desire to achieve (maintain) a possible (satisfactory) level of development. Under such conditions, the quantitative assessment of motivation is defined as the magnitude of the deviation between the possible (satisfactory) level and the real one.
3. To take into account socio-economic features, an economic interpretation of the Weber-Fechner psychophysiological law was proposed, which made it possible to formalize motivation in a logarithmic form, which, unlike a linear one, allows taking into account individual (group) features of the socio-economic system under study.
4. An analysis of the constructed models made it possible to identify the presence of a "fatigue point", that is, the moment in time when the growth of economic activity in a given mode ceases to have a critical impact on its potential development. This moment testifies to the possibility (necessity) of increasing the growth rate of production activity due to its technological transformation.
5. The constructed models can be attributed to simulation. They make it possible to study transitional processes within the framework of the concept of sustainable development.
6. According to the authors, the development of a methodology for determining the scale factor will allow taking into account the individual features of the economic behavior of the modeling object.

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References

[1] Ivanov R V, Grynko T V, Porokhnya V M, Pavlov R A and Golovkova L S 2022 *IOP Conference Series: Earth and Environmental Science* **1049**(1) 012041 URL https://doi.org/10.1088/1755-1315/1049/1/012041
[2] Klarin T 2018 *Zagreb International Review of Economics and Business* **21**(1) 67–94 URL https://doi.org/10.2478/zireb-2018-0005
[3] Barbier E B 1987 *Environmental Conservation* **14**(2) 101–110 URL https://doi.org/10.1017/S0376892900011449
[4] Brundtland G H 1987 *Environmental Conservation* **14**(4) 291–294 URL https://doi.org/10.1017/S0376892900016805
[5] Amegah A K and Jaakkola J J K 2016 *Bulletin of the World Health Organization* **94**(3) 215 URL https://doi.org/10.2471/BLT.15.155812

[6] Isayev R O 2020 *Vyatka State University Bulletin* (2 (136)) 32–42 URL https://tinyurl.com/2yezthsd
[7] Lavrov E, Paderno P, Burkov E, Volosiuk A and Lung V D 2020 *E3S Web of Conferences* **166** 11002 URL https://doi.org/10.1051/e3sconf/202016611002
[8] Dalevska N, Khobta V, Kwilinski A and Kravchenko S 2019 *Entrepreneurship and Sustainability Issues* **6**(4) 1839 URL https://doi.org/10.9770/jesi.2019.6.4(21)
[9] Porokhnya V, Shertennikov Y, Ivanov R and Ostapenko O 2020 *E3S Web of Conferences* **166** 13001 URL https://doi.org/10.1051/e3sconf/202016613001
[10] Ougolnitsky G and Usov A 2018 Sustainable management in regional fisheries: Mechanisms of motivation of myopic agents *Proceedings of the International Scientific Conference "Competitive, Sustainable and Secure Development of the Regional Economy: Response to Global Challenges" (CSSDRE 2018)* (Atlantis Press) pp 69–73 ISBN 978-94-6252-514-6 ISSN 2352-5428 URL https://doi.org/10.2991/cssdre-18.2018.16
[11] Pan L, Yang F, Lu F, Qin S, Yan H and Peng R 2020 *Sustainability* **12**(5) 2070 URL https://doi.org/10.3390/su12052070
[12] Cui H, Wang R and Wang H 2020 *Journal of Cleaner Production* **269** 121799 URL https://doi.org/10.1016/j.jclepro.2020.121799
[13] Hudzynskyi O, Hudzynska Y, Sudomyr S and Sudomyr M 2019 Methodological Aspects of Forming Mathematic Models of Management of Socio-economic Systems Development *Modern Development Paths of Agricultural Production* ed Nadykto V (Cham: Springer International Publishing) pp 441–449 ISBN 978-3-030-14918-5 URL https://doi.org/10.1007/978-3-030-14918-5_45
[14] Malinetskiy G 2005 *Mathematical foundations of synergetics* (KomKniga Publisher)
[15] Cronin J 2007 *Ordinary Differential Equations: Introduction and Qualitative Theory* 3rd ed Chapman & Hall/CRC Pure and Applied Mathematics (CRC Press)
[16] Zakari Y and Hassan A 2019 *Annals. Computer Science Series* **17**(1) 57–62 URL http://anale-informatica.tibiscus.ro/download/lucrari/17-1-07-Zakari.pdf
[17] Almeida R, Bastos N R O and Monteiro M T T 2018 *Statistics, Optimization & Information Computing* **6**(1) 4–11 URL https://doi.org/10.19139/soic.v6i1.465
[18] Madsen J B, Robertson P E and Ye L 2019 *European Economic Review* **118** 51–68 URL https://doi.org/10.1016/j.euroecorev.2019.05.004
[19] Naso P, Lanz B and Swanson T 2020 *European Economic Review* **128** 103499 URL https://doi.org/10.1016/j.euroecorev.2020.103499
[20] North D C 1990 *Institutions, institutional change and economic performance* (New York: Cambridge University Press) URL https://doi.org/10.1017/CBO9780511808678
[21] Haken H and Portugali J 2016 *Entropy* **18**(6) 197 ISSN 1099-4300 URL https://doi.org/10.3390/e18060197
[22] Akhmedov R 2021 *International Journal of Progressive Sciences and Technologies* **24**(1) 11–14 ISSN 2509-0119 URL https://ijpsat.org/index.php/ijpsat/article/view/2510
[23] Gatto M, Muratori S and Rinaldi S 1988 *Ecological Modelling* **42**(2) 155–159 ISSN 0304-3800 URL https://doi.org/10.1016/0304-3800(88)90113-5
[24] Alvarez E L H R and Hening A 2022 *Stochastic Processes and their Applications* **150** 678–698 ISSN 0304-4149 URL https://doi.org/10.1016/j.spa.2019.02.008
[25] Svetlosanov V A, Kochurov B I, Nizovtsev V A and Zhagina S N 2021 *Problems of regional ecology* (1) 41–46 URL https://doi.org/10.24412/1728-323X-2021-1-41-46
[26] Ivanov R V 2014 *Ekonomichnyi prostir* **81** 64–72 URL http://nbuv.gov.ua/UJRN/ecpros_2014_81_9
[27] Nisticò S 2021 *The European Journal of the History of Economic Thought* **28**(4) 635–653 URL https://doi.org/10.1080/09672567.2020.1862270
[28] Usman M and Hammar N 2021 *Environmental Science and Pollution Research* **28**(12) 15519–15536 ISSN 1614-7499 URL https://doi.org/10.1007/s11356-020-11640-z
[29] Ahmad M, Jiang P, Majeed A, Umar M, Khan Z and Muhammad S 2020 *Resources Policy* **69** 101817 ISSN 0301-4207 URL https://doi.org/10.1016/j.resourpol.2020.101817
[30] Fernández-Huerga E 2008 *Journal of Economic Issues* **42**(3) 709–726 URL https://doi.org/10.1080/00213624.2008.11507175
[31] Copelli M, Roque A C, Oliveira R F and Kinouchi O 2002 *Phys. Rev. E* **65**(6) 060901 URL https://link.aps.org/doi/10.1103/PhysRevE.65.060901

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Tools for the formation of a "favorable environment" for organic production as a prerequisite for the sustainable development of agriculture in Ukraine

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Abstract. The significance of protection of environmental components (soil, water, air, biodiversity, landscape) in global aspect directs the development towards sustainable agriculture, and organic production in particular. Organic production as a way of achieving sustainable growth is determined in the three main aspects of sustainable development: economic, social and ecologic sustainability. The conducted in the article analysis of statistical data on the development of domestic market of organic agricultural products shows that organic production in Ukraine is developing at a fast pace and stays one of the priorities for the further development of agro-industrial complex. At the same time, difficult current conditions of functioning of domestic organic enterprises can influence negatively the further development of this sphere, that will result in decrease of organic products export and will have negative impact on food security of other countries. Considering the mentioned, the purpose of the article is the substantiation of tools and measures which will ensure the formation of favorable environment for conducting organic production in the war and post-war periods. With the aim of systematization of the tools for the formation of "favorable environment" for the development of organic agricultural production their study is conducted with further grouping into regulatory and legal, political, stimulating and compensatory, fiscal and restrictive, financial and investment, infrastructural, informational, social and cultural, marketing, and digital. In the course of further research, within each group of tools a specific list of measures that must be implemented to simulate the development of organic agriculture and the circle of subjects responsible for their implementation were determined. It was proven that the formation and implementation of the defined tools and measures should take place at the international, national, regional, and local levels. The content characteristics of each group of tools, which are highlighted in the article, are important guidelines for the formation of effective state social and economic policy and international cooperation development in the conditions of aggravation of influence of global challenges and provide the certain opportunity for definition of ways of their improvement.

1. Introduction

Within the framework of sustainable development concept, the scientific and expert environment offer to implement the set of balanced goals and strategies of regional, national, and industrial development, aimed at solving modern ecological, economic, and social challenges, that acutely faced humanity [1]. Today, the issue of environmentalization of world countries' economies as well as of Ukraine's economy is especially relevant. In our country the processes of environmental pollution as a result of military operations take place in many regions of the country, and the natural environment changed by man does not always have a positive effect on society.

The importance of this problem, among other things, is related to the growth of the world population and the need to solve threats to food security, as well as to the climate changes. One of the ways of solving the mentioned problems is the implementation of environmentally safe ways of agricultural production, namely organic production [1]. It is organic agriculture that provides an opportunity to agree and harmonize environmental, economic, and social goals in the agricultural sector of the Ukrainian economy [2].

Organic production as a way of achieving sustainable growth is determined in the three main aspects of sustainable development: economic sustainability – increasing competitiveness, strong market orientation and increased incomes; social sustainability – bigger responsibility towards consumers' demands, improving food quality and safety; regional development; ecologic sustainability – unified framework, effective implementation and control, standards of protection of environment and health [3].

The essence of the concept of "organic production" is revealed in a number of regulatory documents. According to the law of Ukraine "On the main principles and requirements towards organic production, circulation and labelling of organic products", organic production defined as the certified activity that involves production of agricultural products (covering all stages of technological process, namely primary production (including harvesting), preparation, handling, mixing and procedures related to it, filling, packing, processing, recovery and other alterations to the state of the products), performed in compliance with legal requirements in the sphere of organic production, circulation and labelling of organic products [4].

EU Commission Regulation 2018/848 defined organic production as an overall system of farm management and food production that combines best environmental and climate action practices, a high level of biodiversity, the preservation of natural resources and the application of high animal welfare standards and high production standards in line with the demand of a growing number of consumers for products produced using natural substances and processes [5].

Thus, the requirement for organic agriculture include not only compliance with environmental standards of product purity, but also of the environment. It ensures the balanced state of ecological system, which is the basis for sustainable development of economic and social sphere.

World experience proves that the introduction of environmentally friendly technologies in the production of agricultural products allows to increase the level of their profitability and competitiveness, reduce the production costs of enterprises, create a basis for environmentally safe development of the economy, additional jobs in rural areas and new prospects for small and medium-sized farms, to raise the standard of living and health of the population, to switch to a scientifically substantiated system of land use, etc.

Furthermore, organic production is considered in two aspects of protection: environmental protection by using management practices that do not have adverse effects on environment, and the health of consumers – by the provision of organic products [6].

The development of various laws, regulations, programs, and concepts is a significant confirmation of the acuteness of the raised problem regarding the need to activate environmentally oriented entrepreneurship for the purpose of sustainable development of agriculture. On March 3, 2021 the Cabinet of Ministers of Ukraine approved "The National Economic Strategy until 2030", which officially sets the goal for % of land under organic production. According to the strategy, it is planned that the percentage of lands with organic status should be at least 3 % (now, this figure is 1 %) of the total area of agricultural lands in Ukraine, which is approximately 1.3 million hectares [7]. The European Union intends to increase the organic farming area up to 25 % by 2030 (now, this figure is 8 %). Simultaneously, at least 10 % of agricultural land should be converted into "living areas" with a high biological diversity [8].

Thus, the expediency of implementation and spread of organic production in the world as well as in Ukraine is beyond any doubt. At the same time, in order to promote the development of domestic organic agriculture, it is necessary to create a favorable environment through the justification and implementation of appropriate tools, taking into account the effect of martial law on the territory of our country.

2. Literature review

The scientific and applied problems of the development of organic agriculture were constantly in the field of view of many Ukrainian and foreign scientists. Thus, Shkuratov et al [2] dedicate their work to the study of theoretical and methodical foundations of ecological and economic prerequisites of organic agriculture development. The authors propose the ways of increasing the efficiency of production of organic agricultural products and substantiate the directions of formation of a system of ecological and economic imperatives of the development of organic agriculture, which should become a guideline for the state government and local self-government during the design of the organic farming development program.

Shulyak [9] defines the following tool of regulating and activating of ecologically oriented entrepreneurship on rural territories: coercive-restrictive, stimulating and compensatory, financial, informational, social and psychological, market (marketing). In the opinion of the author, the configuration of the outlined measures, focused on a three-level system of formation and implementation (national, regional, local levels), will enable the coordination of environmental and economic interests of business entities.

Hranovska [10] substantiates the necessity of formation of the mechanism of stimulating of organic production by agricultural enterprises on the basis of implementation of following tools: subsidial (preferential crediting, preferential taxation, budget payments, compensations, subsidies, price premiums, co-financing of scientific and research developments); infrastructural (creation of production and sales chains, development of rural territories, formation of laboratories and quality assessment centers, conduction of marketing research, activation of various economic agricultural formations); informational (establishment of information centers, public organizations, development of agricultural parks, eco-villages and ethnic centers); legal (certification, insurance, legal aid, activation of development and implementation of state programs for development and stimulating organic production).

The study of Hou et al [11] is one of the few studies that comprehensively examines the impact of macro-level factors on organic production in the U.S. Specifically, this research looks at the determinants including macroeconomic factors, policy factors, demographic factors, and agricultural input factors that cover many aspects of organic farming. The multivariate analytical framework with multiple year data enables this study to examine whether a series of factors can effectively promote organic farming and by how much. This study provides evidence using state-level observations and a robust econometric method to further support the findings of relevant literature.

It should also be mentioned that a significant amount of research is devoted to the issues of state regulation of development of organic production in Ukraine. Thus, Hvozd [12] provides a scheme of organizational and economic mechanism of state regulation of the organic agricultural production market in Ukraine. The author also substantiates its legal (Laws and Resolutions of the Verkhovna Rada of Ukraine, Resolutions of the Cabinet of Ministers of Ukraine, normative acts and state standards of organic production, Private organic standards), normative (institutions, regulations, methodical recommendations), economic (crediting, material and technical support, budget policy, taxation, pricing, agricultural insurance), administrative (antimonopoly policy, standardization, quotas, production certification, environmental control, licensing), institutional support (state authorities, international organizations, associations of enterprises, organizations for the protection of consumer rights, regional bodies of influence on the vector of development of the food sector).

At the same time the relevance of the research in the sphere of organic production development as of an important constituent of sustainable development of rural territories and of a strategically important direction of agricultural business in Ukraine objectively indicates the need for a thorough study of its individual aspects, in particular, regarding the theoretical vision of tools for creating a favorable environment for its management in the war and post-war periods.

3. Objective of the research

The purpose of the research is the substantiation of conceptual foundations of formation of a favorable environment for the development of organic agriculture in Ukraine considering current conditions of martial law. The set purpose involves solving the following tasks: study of the trends of organic production sphere development; identification of tools which have a decisive influence on the formation of a favorable environment for the development of organic production; substantiation of specific measures within individual tools and definition of the subjects responsible for their implementation.

4. Results

Today, organic production is developing in almost all countries of the world and is promising for further development in Ukraine as well. Constantly growing consumer demands for organic products, as well as the global trends towards sustainable farming, allow Ukraine to be the active participant in the world organic market. The organization of the effective output of organic products in the management system of the agrarian nature remains relevant and is considered as one of the major ways of the agricultural production ecologization [13].

According to the latest operational monitoring data which the Ministry of Agrarian Policy and Food of Ukraine (MAPF) collected from certification bodies that certified organic production and circulation of organic products in Ukraine (EU Regulation and NOP) as of the end of 2021, the total area of organic and inconversion agricultural lands in Ukraine was 422,299 hectares (including organic agricultural area 370,110 hectares). Organic agricultural land remains 1 % of the total agricultural area in the country. The number of organic operators in 2021 was 528, with 418 agricultural producers among them [14]. These operators include producers, processing companies, importers, and exporters of organic products (figure 1).

Over the past four years, the number of organic operators has been on a downward trend (table 1). In particular, in 2021, compared to 2020, their number decreased by 21 units (or by 3.8 %).

The data show that during 2016-2020 the area of agricultural lands with organic status has increased more than 2 times (by 104.3 %). But in 2021 the decrease of the land area by 9.9 % (26054 ha) is observed comparing to the previous year.

Unfortunately, it is expected that the area of organic lands will shrink in 2022 as a significant part is occupied in the southern regions of the country. Since the beginning of the full-scale war, about 120,000 hectares of certified organic land were lost, especially in Kherson and Zaporizhzhia oblasts [14].

As for the Ukraine's organic domestic market it has been growing slowly but steadily, despite different challenging economic circumstances. A total of 9,780 tons of organic products (which is 11.4 % more than in 2020) at a value of UAH 900 million are estimated to have been sold on the domestic market in 2021, equivalent to 33 million USD at the National Bank of Ukraine exchange rate as of December 31, 2021.

Even though Ukrainians consume much less organic products (less than 1 euro per capita) than residents of EU countries and Switzerland, the interest in more natural and healthy foods has been growing [14].

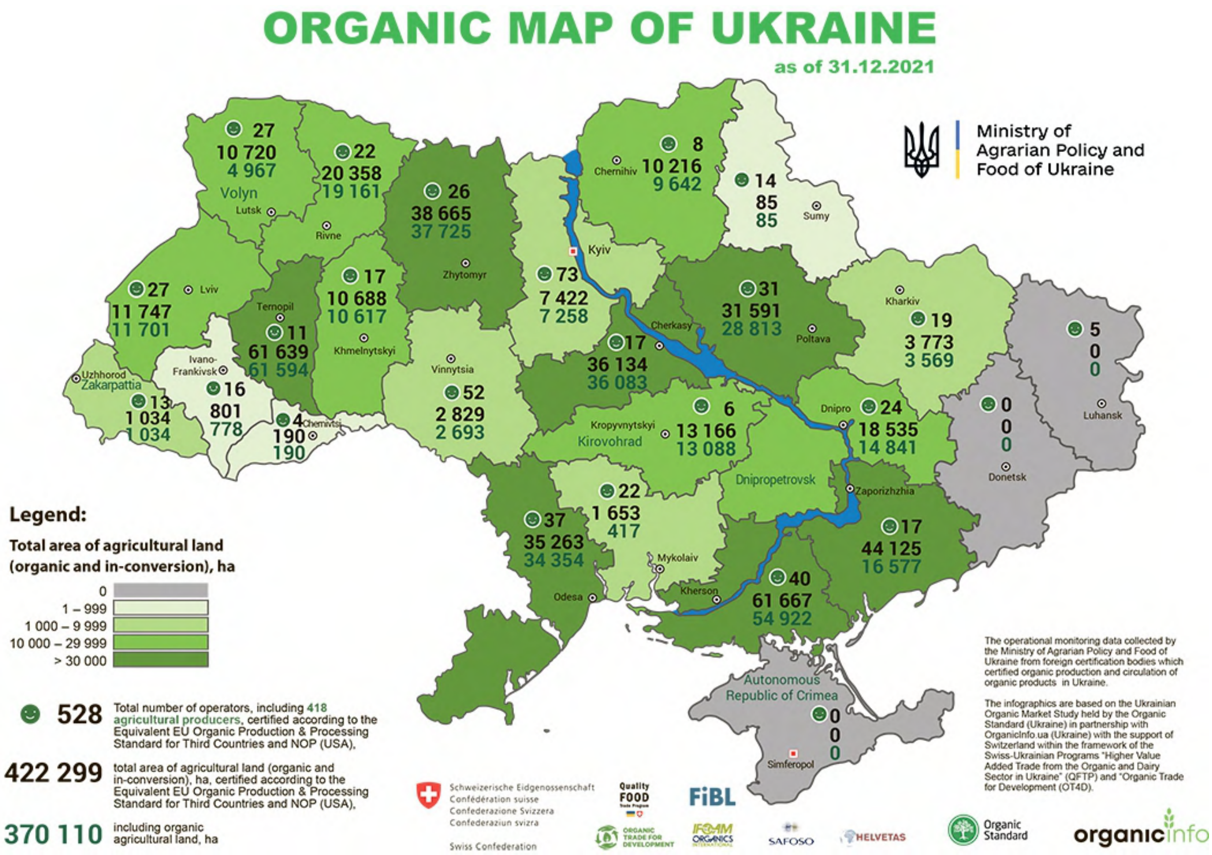

Figure 1. Organic map of Ukraine, as of December 31, 2021 [15].

Table 1. Organic production in Ukraine for 2016-2021 [16].

Indicator	Years					Deviation, %	
	2017	2018	2019	2020	2021	2021 to 2017	2021 to 2020
Number of organic operators:							
total number of operators	504	635	617	549	528	4.76	-3.83
including agriculture producers	304	501	470	419	418	37.50	-0.24
Area of agricultural land, hectares:							
total area of agricultural land (organic and in-conversion)	289000	309100	467980	462225	422299	46.12	-8.64
organic agricultural land	201000	233500	384529	410583	370110	84.13	-9.86
Sales of Ukrainian organic products, million USD:							
domestic market, million USD	-	21	24	26	33	57.14*	26.92
tons	-	6700	7350	8778	9780	45.97*	11.41
export market:, million USD	102	157	189	204	222	117.65	8.82
tons	254000	390000	469000	332000	261000	2.76	-21.39

* Deviation 2021 to 2018, %

In recent years, Ukraine has consolidated its position as a world leader in the supply of organic products to the EU as well as an important player for other international organic markets and has taken an important place in ensuring a sustainable food system and food security in the world [14]. Thus, in 2021 Ukraine exported about 261,000 tons of organic products worth USD

222 million to over 30 counties, 82 % of which were exported to the EU [15].

At the same time in 2021 Ukraine slightly reduced the export volumes to the EU (189,239 tons in 2021 compared to 217,210 tons in 2020), but it still remained among TOP 5 organic suppliers to the EU. The total share of Ukrainian organic imports was 6.6 % in 2021.

As for the imports from Ukraine, it ranked No 1 by organic import volumes of cereals (other than wheat and rice), and was among TOP 3 suppliers of oilcakes, oilseeds and soybeans. In addition, Ukraine moved up into the second place by organic import volumes of fruit (fresh or dried fruit and berries, excluding citrus and tropical fruit).

The full-scale war that Russia started against Ukraine in 2022 caused colossal losses to the organic sector, however, it did not prevent Ukraine from maintaining its leadership position in the export of organic products. Thus, despite the temporary occupation of one-third of the organic land, hostilities, and problems with logistics, during the 8 months of 2022, Ukraine exported 24 % more organic products compared to the same period in 2021 [14].

Today the development of organic market in Ukraine is one of the priority directions of the agriculture development. Statistical data evidences that our country has reached certain results in the development of its own organic production, possessing favorable conditions for organic agriculture, including the size of the country, geographical location, proximity to potential export markets, large area with fertile soils.

At the same time, since the beginning of Russia's full-scale invasion of Ukraine on February 24, the Ukrainian organic sector, and the entire agrarian industry, has been suffering from Russian aggression. Problems include occupied land; mined fields; destroyed farms, warehouses, and infrastructure; lack of fuel and vehicles; and domestic demand that has nosedived. After the Northern regions and some districts in the Southern regions were liberated, organic operators started to resume their activities there, and some of them relocated their businesses to other regions. Organic producers in other regions did not stop their activities or stopped for a very short time.

Organic production as a sector having a great potential for making significant contributions to sustainable development (and thus put as a priority in a number different levels, especially by the European Union and international community) leads to various positive influences on environment, society and economy [17].

Considering the above, the urgent issue is the creation of a "favorable environment" for functioning of organic production with the purpose of formation of an effective strategy for its development in the conditions of martial law, aimed at the production of environmentally safe products, increasing the competitiveness of agricultural entities in the internal and foreign markets.

In accordance with the Protocol on Sustainable Development of Agriculture and Rural Areas to the Framework Convention on the Protection and Sustainable Development of the Carpathians, "favorable environment" is a complex of interrelated conditions, such as: legal, organizational, fiscal, informational, political, and cultural which contribute to sustainable and efficient use of participants' opportunities in development processes. In this document it is also defined that "sustainable agricultural and rural development" is a management and conservation of the base of natural resources, as well as orientation of technological and institutional changes in order to ensure the achievement and constant satisfaction of human needs of the present and future generations [18].

Shkuratov et al [2] have provided the systematization of the factors of impact on the development of organic agricultural products, which is based on their division into four main functional groups according to the following characteristics: organizational and legal, financial and economic, technological, and social and psychological, and provides the opportunity to improve and form efficient measures of the development and implementation of the organic agricultural products system taking into account the sphere of influence of such factors.

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In general, the conducted literature review shows that scientists have not formed a single approach to the systematization of tools that must be used to create a favorable environment for the development of organic agriculture.

Taking into account the existing views of scientists and the current complex conditions of the functioning of organic enterprises, we consider it necessary to highlight the following tools that have a decisive influence on the formation of a favorable environment for the development of organic agriculture in Ukraine (table 2).

Table 2: The tools which affect the formation of a "favorable environment" for organic agriculture development.

Tools	Measures	Responsible subjects
Regulatory and legal	Further development of the legislative and regulatory framework of regulation of relations in the sphere of production, circulation, certification, and labeling of organic agriculture products. Further harmonization of Ukrainian legislative framework with the requirements of European legislation. Activation, development, and implementation of state and regional programs for development and stimulation of the organic production.	State
Political	Development of international cooperation, including international trade; further cooperation with projects of international technical aid in the sphere of organic production.	State, international partners
Stimulating and compensatory	Provision of financial assistance in the form of targeted subsidies and grants, preferential taxation, preferential crediting, special insurance regime, financing (at least partial) of socially important organic projects and programs, full or partial repayment of the cost of certification services, co-financing of scientific R&D.	State, financial and credit institutions
Fiscal and restrictive	Introduction of environmental payments, licensing, financial sanctions for violations of environmental regulations, taxes, fees, fines, etc.	State
Financial and investment	Formation of the specialized investment funds, environmental banks and programs; development of environmental insurance.	State, international partners, investors (internal and external), economic entities
Infrastructural	Creation of production and sales chains, development of rural territories, formation of laboratories and quality assessment centers, activation of various economic agricultural formations, creation of an extensive system of certification bodies.	State, international partners, non-governmental organizations, economic entities

Continued on next page

Table 2 – continued from previous page

Tools	Measures	Responsible subjects
Informational	Providing free access for economic entities to the regulatory base in the sphere of organic production and products circulation, formation of local environmental information and consulting centers; establishment of public organizations, environmental consulting, information dissemination among the consumers and operators and creation of a system of cooperation between them on the entire production chain – from the economic entity to the consumer.	State, international partners, non-governmental organizations, economic entities
Social and cultural	Formation of the environmentally and socially oriented corporate culture and responsibility, environmental ethics and consciousness of the entrepreneur and of the society as a whole; activation of environmental education; orientation on production and consuming of natural products.	Economic entities, non-governmental organizations, state (institutions of education, culture, upbringing, health)
Marketing	Popularization of organic production based on the organization of various events (exhibitions, fairs, conferences, etc.) to promote organic agriculture in the internal and foreign markets. Formation of the organic products market; development of ecological marketing; creation of ecological brands.	State, economic entities, non-governmental organizations, international partners
Digital	Saturation of agricultural business with such modern digital technologies as the Internet of Things, artificial intelligence, the use of big data (Big Data), robotization of production and management processes.	State, international partners, investors, economic entities

Legal regulation consists in the development and adoption of laws, regulations, resolutions, requirements, and standards that establish legal, economic, social, and environmental rules for the cultivation, production, processing, certification, transportation, storage and sale of organic products. It is also responsible for fair competition on the market of organic products.

During last years government together with public organizations and international projects has been working on the improvement of legislative and regulatory framework. In particular, a set of legal documents was adopted, as well as amendments to the current legislative acts that regulate the sphere of certification and labeling of organic products in Ukraine were made [19]. A significant landmark for Ukrainian organic legislation occurred in 2021, when amendments to the Law of Ukraine No 2496-VIII "On the main principles and requirements towards organic production, circulation and labelling of organic products" came into force. Together with the Law, adopted on July 10, 2018, this is the legal foundation of organic production, circulation, and labelling of organic products in Ukraine [14]. Earlier manufacturers certified their production according to the legislation of other countries, mainly the EU. Now Ukraine will have its own certification system in accordance with national legislation. Such changes contribute to the development and transparency of the domestic organic sector and to the improvement of

Ukraine's image in the world trade arena. At the same time, one of the urgent tasks is the further harmonization of Ukraine's legislation on the organic products manufacturing with the world certification systems. The compatibility of such systems will make it possible to expand the external market of organic products [19].

Besides it, considering European orientation of Ukraine and difficult conditions of functioning of domestic organic producers, there is an urgent need to develop and adopt national and regional programs for the development of organic production in Ukraine, as an environmentally, socially, and economically expedient direction of production activity.

The implementation of political instruments is manifested in the fact that the development of the Ukrainian organic sector has been also supported by different countries within international programs/projects of technical support. Representatives of these projects take an active part in the development of a legal framework that will effectively regulate the process of organic production. The largest of such projects are Project "German-Ukrainian Cooperation in Organic Agriculture" (COA) – Phase II, implemented by AFC Consultants International / IAK Agrar Consulting GmbH and funded by the German Federal Ministry of Food and Agriculture (BMEL); Swiss-Ukrainian Program "Higher Value Added Trade from the Organic and Dairy Sector in Ukraine" (QFTP) implemented by the Research Institute of Organic Agriculture (FiBL) in partnership with SAFOSO AG and supported by Switzerland; Swiss-Ukrainian Program "Organic Trade 4 Development in Eastern Europe" (OT4D) supported by the Swiss State Secretariat of Economic Affairs (SECO) implemented by the IFOAM – Organics International in consortium with HELVETAS Swiss Intercooperation and Research Institute of Organic Agriculture (FiBL) and supported by Switzerland and other [14]. It should be noted that thanks to the Swiss support Ukraine has managed to establish a committed organic stakeholder network with its own Organic Standard control body, Ukrainian organic web portal OrganicInfo, organic national policy dialogue, and agreed on the joint vision for Ukrainian organic sector development through Organic Initiative.

Under terms of martial law, the government attention should be concentrated on the creation of the conditions for international trade implementation, particularly, on finding export opportunities, new logistic solutions for supplying Ukrainian organic products to other countries, expanding sales markets. Solving these problems is possible due to system and effective cooperation of Ukrainian government and international partners. Efforts in the political arena should be directed to this. Despite the full-scale war and threats for the country Ukraine proceeds to contribute largely to the world's food safety. In particular, the sowing campaign of 2022 was carried out, alternative logistics routes were developed for the supply of Ukrainian agricultural products abroad. Considering the above, with the help of political instruments it is necessary to create conditions for the export of Ukrainian organic products through lobbying at the political level and promotion on the international arena, as well as solving the urgent needs of exporters of organic products.

With the help of stimulating and compensatory, and fiscal and restricting tools the state motivates manufacturers to production of organic agricultural products and establishes certain sanctions for violators of environmental norms in general and organic production requirements in particular with the aim of ensuring the presence of high-quality organic products on the market.

A system of grants, dotations, provision of land plots at a discounted price, etc. can be material incentives for manufacturers of organic products. Considering the complex economic conditions of functioning, implementation of these tools is one of the main stimulating factors, which contributes to the decision to switch to organic production.

It should be mentioned that currently the work in this direction continues. Thus, Organic Initiative launched the grant program "Support for the Organic Sector in Ukraine". The grant program's purpose is to support organic producers to overcome the current situation and preserve and strengthen the organic sector's capacity in the mid- and long-term. According to the results of the grant program's (two phases), about 120 organic market operators received support for a total amount of about 350,000 USD to cover costs for organic certification, purchasing organic food products from organic producers (with further distribution among IDPs, vulnerable populations, etc.), purchasing inputs, further development of the marketing activities at the domestic market, purchasing equipment, etc. A significant proportion of this support was provided by OT4D and QFTP programs [14]. Within the fundraising campaign of the Future Foundation for Agriculture "Support for Emergency Aid Ukraine Organic Farming" 170 enterprises were supported, among them organic producers and organizations of the organic sector in total 560,000 Euro [20].

Implementation of the appropriate mechanisms for realization of functioning of the defined stimulating and compensatory tools for market operators should provide the access of organic products manufacturers to additional and released financial resources, at the expense of which they will be able to repay the received loans on time, to implement into production innovative technologies, aimed at increasing the ecological characteristics of the products and decreasing the environment pollution, to start timely the process of product certification according to organic standards, and in the future to reduce gradually the cost of products for the final consumer. All this will have a positive impact on the formation of investment attractiveness of the organic production enterprises, as well as will promote activation of their activity [21].

At the same time, in case of violation by producers of organic products of ecological requirements, penalties should be applied to them in the form of additional payments for environmental pollution, fees for non-compliance with cultivation technologies, fines for low-quality food products, deprivation of certification with the obligation to return funds for their certification, other financial sanctions. The set of fiscal and restrictive tools of state policy should be preventive in nature and should be aimed at ensuring compliance with production technology at all its stages by organic enterprises, in order to provide the production of high-quality and environmentally safe products.

Financial and investment tools should be singled out in a separate group, the implementation of which consists in the formation of specialized investment funds, environmental banks and programs; development of environmental insurance. The financial platform for the development of domestic environmentally oriented entrepreneurship is formed by special investment funds (institutional measures designed to direct targeted cash flows (income, profit) for the purposes of environmental protection and improvement), environmental banks and environmental programs. In addition, environmental business insurance (voluntary or state mandatory), i.e. civil liability insurance of business entities for damage caused as a result of economic activity, which causes increased environmental danger, is relevant and effective in modern conditions. Such a financial tool is a powerful method of encouragement and, at the same time, provides a condition for economic stimulation of business entities to function without harming the natural environment, or at least with minimal impact on it [9].

The results of the Organic Ukraine NGO survey of Ukrainian organic businesses, conducted in mid-March 2022, showed that 30 % of Ukrainian organic operators had to suspend their business activities and 70 % required financial support [14]. That is why the issue of activation of financial and investment instruments for the development of organic production is currently acute.

Infrastructural tools for the formation of favorable environment should be aimed at ensuring higher quality and more effective process of implementation of chain "production – distribution – sale", as well as at more efficient marketing policy for the system functioning of the organic agricultural production. Measures that must be implemented within this group of tools include:

- creation of production and sales chains (first of all, the stress must be put on the objective formation of the organic chain and joint responsibility of the "producer – trader – certification body – state authorities" system);

- rural territories development (purposeful change of institutional, economic, ecological, demographic, social, cultural, household, and other most important factors that determine directions and directly affect the growth of the level and quality of life of the rural population and ensure the prevention or overcoming of poverty);
- formation of laboratories and quality assessment centers (formation of modern laboratories to assess the quality and safety of organic products, their analysis for compliance with current standards);
- activation of various economic agricultural formations – participation in programs of development of organic production, communication with organic producers of global markets, etc.;
- creation of an extensive system of certification bodies.

The formation of the necessary conditions for free access for economic entities to the ecological information, regulatory base, environmental passporting, programs of financial support, etc. is provided by informational tools. An important component is the formation of local information and consulting centers, the goals of which should be: shaping the environmental consciousness of citizens, providing environmental consulting, dissemination of the relevant information on the actual state of environment, popularization of the best practices of balanced development, introduction of environmental technologies, organization of different trainings, round tables, educational business seminars for different categories of participants – children and youth, students, educators, representatives of amalgamated territorial communities, employees of local self-government bodies, etc. [9].

Adequate public awareness can ensure support for government decisions that may otherwise be unpopular (for example, decisions to raise prices for natural resources or redirect public resources to improve the environment) [2].

An equally important role in creating a favorable environment for the development of organic agriculture is played by social and cultural tools, namely environmentally and socially oriented corporate culture and responsibility; activation of environmental education, especially in higher educational institutions; environmental ethics and consciousness of the entrepreneur and the whole society. Their implementation should promote increasing the level of professional knowledge, experience, and research in the respective economic sphere through the introduction of appropriate training courses on the theory and practice of organic production in educational institutions of various accreditation levels, the creation of modern research farms and the improvement of training of farmers and controllers. It is also necessary to choose several farms in each region, which would become pilots in the organization of agricultural production.

The popularization of organic production in Ukraine is important for formation of favorable environment of development and promotion of organic agriculture. Such popularization should be made on the basis of implementation of marketing tools and organization of various events: exhibitions, fairs, forums, seminars, conferences, etc.

It should be noted that Ukrainian agrarian sector was very active during all these years and organized a lot of events for promotion of organic agriculture. From year to year, the Ukrainian organic service providers in cooperation with each other, under the patronage of state and regional authorities organize numerous annual events to promote organic agriculture in the domestic market, usually supported by international development partners. Thus, the Organic Ukraine NGO hosted the “Organic Ukraine Regional Forums”, which engaged all 24 Oblast State Administrations to the event organization in 2020 and 2021. For the 5th time, the International Congress Organic Ukraine11 and the 7th Organic Processing and Trade Conference12 were co-organized by Organic Ukraine, Organic Standard and Information Center “Green Dossier” in 2021. The Organic Federation of Ukraine organizes a specialized exhibition “ORGANIC” within the framework of the International Agroindustrial Exhibition “AGRO” which is always accompanied by a special Organic Conference. Organic Products Fair was organized for the 11th time in Kyiv by the Organic Federation of Ukraine.

In these times, it is crucial that the international community knows and sees that Ukraine, its agricultural sector, and the organic sector in particular are operational, have a strong commitment to continue their organic production and trade, and have a positive attitude despite all the wartime difficulties. It is important for the whole country to prove that Ukrainian exporters can fulfil their contract obligations, regardless of various panicked information that is in the media about export disruptions from Ukraine, in order not to lose existing partners and to attract new ones. Therefore, on June 23, the EEPO, Organic Initiative, and other partners with Swiss support (QFTP and OT4D) held the international online event “Organic Export During the War” in order to provide existing and potential partners of Ukrainian exporters from abroad with reliable up-to-date information about the market condition and its capacities [14].

Today’s relevant requirement is the digitalization of business-processes, including those in the sphere of organic production. At the same time, there should be a reduction in the use of manual labour in agricultural production and the saturation of agricultural business with such modern digital technologies as the Internet of Things, artificial intelligence, the use of big data (Big Data), robotization of production and management processes. Innovative digital tools that should be widely used in the sphere of organic production include the following:

- 3D-printing technologies (the use of such innovative tool will allow to upgrade tools for repairing agricultural machinery, to use 3D parts during capital and ongoing repair of equipment);
- blockchain technologies, with the help of which the consumer has the opportunity to access transparent and open information about the origin, production, processing, and transportation of the products he consumes. Such technologies make it possible to control the origin, quality, environmental friendliness of agricultural raw materials and food;
- GNSS – Global Navigation Satellite System, which contributes to increasing the quality of performance of all technological operations in crop production;
- the use of unmanned aerial vehicles and drones helps to carry out quality monitoring of soil condition, the level of quality of performed agricultural operations, and allows to predict the volume and quality of agricultural crops harvest as accurately as possible.

The effects of digitalization of agricultural activities envisage all three approaches of sustainability – economic, ecological and social; they are interdependent and synergic.

Each of the mentioned above groups of tools influences the level of saturation of the market with organic products, restraining or promoting its development.

Formation of the tools and means of influence on the processes of development of environmentally oriented entrepreneurship should be performed on the principles of systematicity, economic expediency, compromise, security, environmental responsibility, monitoring and control. Involving economic, ecological, organizational, regulative, and financial mechanisms and influence levers with the use of different implementation methods will allow to obtain synergetic effect from their implementation.

5. Conclusions

In order to provide the concept of agricultural production sustainable development in Ukraine and in the world at the current stage, while forming a military economy, choosing a strategy for the development of business entities in the post-war period, it is necessary to concentrate not only on obtaining profits, but also on taking care of the preservation of the environment and the social development of society. The organic agricultural production direction is one of the perspective ways of development of agricultural sector of economy, which will allow any country to achieve sustainable social and economic development, and a set of other advantages. Organic production allows to implement the concept of balanced development of the agricultural sphere on the basis of social and economic, natural and resource balance and aims to provide society with safe and high-quality food products, as well as to preserve and improve the state of the environment.

The conducted research shows that Ukrainian organic products are perspective for export to the EU countries and globally. At the same time, compared to global trends, due to the negative impact of a number of subjective reasons, the development of Ukrainian organic agricultural production lags behind significantly, that may form a negative influence on the export potential of the country and on the volumes of organics supplies abroad. Considering this, the development of organic agricultural production requires the creation of a favorable environment for producers and consumers of organic products, aimed at supporting this direction, which will include both direct and indirect stimulation tools.

The scientific novelty of the research consists in the systematic solution of the important scientific problem about the formation and improvement of tools and measures, the complex implementation of which will provide for creation of the favorable environment for development of organic agriculture. The author also defined the circle of responsible persons who should contribute to the implementation of outlined tools and measures.

The research of the tools for the formation of a "favorable environment" for organic agricultural production development is conducted by the author with the aim of their systematization and further grouping into regulatory and legal, political, stimulating and compensatory, fiscal and restrictive, financial and investment, infrastructural, informational, social and cultural, marketing, and digital. During the detailed analysis the necessity to implement these tools in complex was proven. The implementation of the proposed tools will contribute to the development of organic agricultural production, increasing the efficiency of activities of agricultural enterprises and their competitiveness on regional markets, as well as on the external markets, with simultaneous economic growth, social development, and an increase in the level of environmental security of countries. The content characteristics of each group of tools, which are highlighted in the article, are important guidelines for the formation of effective state economic policy in the conditions of aggravation of influence of global challenges and provide the certain opportunity for definition of ways of their improvement.

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References

[1] Kononenko O M 2017 Organic production in ensuring sustainable development of rural areas *Organic production and food safety* (Zhytomyr: Zhytomyr National Agroecological University) pp 410–415 URL http://znau.edu.ua/images/data2/naukovi_konferencii/materials/organic-2017-pdf.pdf

[2] Shkuratov O I, Chudovska V A and Vdovichenko A V 2015 *Organic agriculture: ecological and economic imperatives of development* ISBN 978-617-7015-27-6 URL https://agroeco.org.ua/wp-content/uploads/Publications/Monography/shkuratov/Shkuratov_a5.pdf

[3] Arabska E 2014 *Organic production: Innovations and sustainability challenges in development framework and management* (LAP LAMBERT Academic Publishing) ISBN 978-3-659-56379-9

[4] Verkhovna Rada of Ukraine 2018 On Basic Principles and Requirements for Organic Production, Circulation and Labelling of Organic Products URL https://zakon.rada.gov.ua/laws/show/2496-19?lang=en#Text

[5] European Parliament and Council of the European Union 2018 *Official Journal of the European Union* **L 150** 1–92 URL http://data.europa.eu/eli/reg/2018/848/oj

[6] Argyropoulos C, Tsiafouli M A, Sgardelis S P and Pantis J D 2013 *Land Use Policy* **32** 324–328 ISSN 0264-8377 URL https://doi.org/10.1016/j.landusepol.2012.11.008

[7] Cabinet of Ministers of Ukraine 2021 Pro zatverdzhennia Natsionalnoi ekonomichnoi stratehii na period do 2030 roku URL https://www.kmu.gov.ua/npas/pro-zatverdzhennya-nacionalnoyi-eko-a179

[8] European Environment Agency 2023 Agricultural area under organic farming in Europe (8th EAP) URL https://www.eea.europa.eu/ims/agricultural-area-used-for-organic

[9] Shulyak B V 2018 *Development of environmentally-oriented business in rural areas* Ph.D. thesis Zhytomyr National Agroecological University Zhytomyr

[10] Hranovska V H 2017 *Economy and society* (9) 384–390 URL https://economyandsociety.in.ua/journals/9_ukr/66.pdf

[11] Hou Y, Luo T and Hao J 2022 *Sustainability* **14**(1) 503 ISSN 2071-1050 URL https://doi.org/10.3390/su14010503

[12] Hvozd O 2019 *European Journal of Economics and Management* **5**(2) 90–96 URL https://eujem.cz/wp-content/uploads/2019/eujem_2019_5_2/14.pdf

[13] Skorokhod I, Skrypchuk P, Shpak H, Chemerys V and Yakubiv R 2022 *Agricultural and Resource Economics: International Scientific E-Journal* **8**(4) 134–150 URL https://doi.org/10.51599/are.2022.08.04.06

[14] Organic initiative 2022 Ukrainian organic sector analysis. 8 months since the full-scale war in Ukraine URL https://organicinitiative.org.ua/en/news/ukrainian-organic-sector-analysis-8-months-since-the-full-scale-war-in-ukraine/

[15] Shor K 2022 Organic production in Ukraine remains one of the priorities URL https://organicinfo.ua/en/news/organic-remains-one-of-priorities/

[16] 2023 Orhanichne vyrobnytstvo Ukrainy za 2016-2021 rr. URL https://organicinfo.ua/infographics/organic-production-in-ukraine-2016-2021

[17] Arabska E and Terziev V 2016 *Journal of Economic Development, Environment and People* **5**(2) 23–30 URL https://www.researchgate.net/publication/291353377

[18] 2020 Protokol pro stalyi rozvytok silskoho hospodarstva ta silskoi mistsevosti do Ramkovoi konventsii pro okhoronu ta stalyi rozvytok Karpat [Protocol on Sustainable Agriculture and Rural Development to the Framework Convention on the Protection and Sustainable Development of the Carpathians] URL https://zakon.rada.gov.ua/laws/show/001_001-17#Text

[19] Melnyk T and Ovander N 2021 *Pryazovsky Economic Bulletin* (5(28)) 79–87 URL https://doi.org/10.32840/2522-4263/2021-5-12

[20] 2022 Successful support of organic farms in Ukraine URL http://coa-ukraine.com/en/news/267-support-organic-eng

[21] Lialina N and Matviienko-Biliaieva G 2019 *Agricultural and Resource Economics: International Scientific E-Journal* **5**(2) 121–140 URL https://doi.org/10.51599/are.2019.05.02.09

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Sustainable development of Ukraine as a combination of social, economic and environmental components: structural econometric model of three-pillar approach

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Abstract. The combination of the economic, social and environmental issues of the country-level development in the case of Ukraine requires modernization of the national economic system and permanent deep institutional reforms. These measures should be aimed at forming a diverse, competitive and socially oriented post-industrial economy capable of ensuring sustainable development. To ensure the improvement of the management of Ukraine's sustainable development strategy, structural (simultaneous) model is proposed, based on three endogenous (namely GDP as economic variable, income per household as social variable and the expenses for the environmental protection as environmental variable) and seven exogenous variables. Such an approach makes it possible to investigate the interdependence between variables. Model parameters estimates were calculated with the two-step least squares method. A forecast of the development of the main indicators characterizing the economic, social and environmental components of development at the country level was also estimated. For Ukraine in 2021, according to the forecast based on the structural model, the economic and environmental components will have positive dynamics and rapid growth, while the social component will develop, but more stably and without rapid growth.

1. Introduction

Before the start of the full-scale war in February, Ukraine was making steady progress in achieving 15 of the 17 Sustainable Development Goals (set of 17 Sustainable Development Goals (SDG) according to the "Transforming our world: the 2030 Agenda for Sustainable Development" [1]), and moreover, it achieved the greatest success precisely in reducing poverty. The first Voluntary National Review of progress towards achievement of the Sustainable Development Goals in Ukraine [2] showed that the main achievement is the reduction of poverty for more then 15 percent during 2015-2018.

Now, when the discussions about the recovery of the country and the economy begin, the SDG are used as a reference point to ensure the most effective reconstruction of Ukraine. The war will require a review of development priorities to achieve the SDG. The interpretation of the 16th SDG – "Peace, justice and strong institutions" will change significantly. SDG 1 "Poverty" will now become a key task of social development. SDG 6 "Clean water and sanitation", which covers ensuring the availability and sustainable management of water resources and sanitation, is becoming urgent. Goal 8 "Decent work and economic growth" becomes of primary importance for the return of Ukrainian refugees.

Undoubtedly, radical changes will have to be made to all state programs, because the focus on sustainable development in the "peaceful" version, where the main priorities are overcoming inequality and a green economy, is being revised even in wealthy democracies. The world is feeling the consequences of the energy crisis, including as a result of the sanctions imposed on Russia, and therefore the governments of the countries are not only postponing the green transition, but also resuming coal mining, taking care of the state of the industry.

Since the problems of sustainable development appear from new perspectives, a reasonable explanation of the dependencies between indicators of sustainable development with mathematical methods will help in making management decisions.

The concept of sustainable development has been spreading during the last decades, but the most popular definition was in the Brundtland report [3]. And while its usefulness may still be questioned (e.g. in Beckerman article [4], it is one of the most popular concepts in terms of popularity. Salvia et al [5] investigated trends in sustainable development research in different levels of investigation. Chabay [6] believes that the greatest success in the implementation of the goals of sustainable development can be achieved by applying interdisciplinary complex systems approaches and trans-disciplinary research methods. Schoenmaker and Stegeman [7] think that the biggest problem in the practical implementation of the concept of sustainable development is the balancing of various goals, unlike, for example, economic concepts that consist in maximizing economic indicators. Vavoura and Vavouras [8] investigated COVID-19 impact on sustainable development and record a significant reduction in the social component of sustainable development in European Union, i.e. an actual return to the concept of economic growth, but on the basis of a green deal.

The concept of sustainable development is implemented at different levels: from the union of countries [9] to country [10, 11], region [12, 13], territorial communities [14] and even family business [15] and enterprises [16].

Regarding the investigation of the sustainable development of Ukraine, the researches of both domestic and foreign scientists are also devoted to this problem. In the article [17] the trends in sustainable development of Ukraine comparing to EU counties is described; in [18] it is considered from the position of the European integration of Ukraine as a strategic goal; Kuzior et al [19] study role of the innovative ecosystem of Ukraine and EU in sustainable development and Sokil et al [20] details innovation ecosystem to startups; Semenenko et al [21] investigate changes in sustainable development before and after the war. Also investigations of the sustainable development of Ukraine are devoted to different aeries, such as agriculture [22], transport [23], rural areas [24] and others.

A wide range of mathematical methods and models are used for quantitative analysis and modeling of sustainable development (table 1). The choice of method depends, among other things, on the purpose of the research. In order to reveal the interdependencies between various indicators that characterize the economic, social and environmental aspects of the country's sustainable development, it is advisable to apply structural modeling methods.

2. Structural equations method for sustainable development modelling

A system of simultaneous equations is a statistical model in the form of a set of simultaneous linear equations. They differ from ordinary regression models in that there are two or more dependent variables.

Variables that are explained by the functioning of the system and whose values are determined by the simultaneous interaction of the links in the model are endogenous variables or jointly determined variables.

Variables that help provide explanations for endogenous variables and whose values are determined outside the model are exogenous variables or predetermined variables. Exogenous variables help explain variations in endogenous variables.

Table 1. Methods and models of sustainable development investigation and modelling.

Authors	Method
Taghvaee et al [25]	vector autoregressive model
Udemba and Keleş [26]	ARDL
Liu et al [27]	ARIMA
de Armas et al [28]	operations research
Wu et al [29]	graph neural networks
Chai et al [30]	fuzzy logic
Moreta et al [31]	text analysis
Zomchak and Starchevska [32]	logistic regression
Holloway and Mengersen [33]	machine learning
Alharbi et al [34]	hierarchical framework
Bielinskyi et al [35]	econophysics
Chen et al [36]	data envelopment analysis
Sutthichaimethee and Ariyasajjakorn [37]	structural equation model
Izonin et al [38]	Wiener polynomial approximation
Horoshkova et al [39]	Kuznets curve
Matviychuk et al [40]	fractal analysis
Valaskova et al [41]	regression analysis

Determining from the data sample those variables which are endogenous and which are exogenous belongs to the model developer himself, that is, in essence, it is partially based on the expert method.

A structural simultaneous model is used to describe the structure of relationships between endogenous and exogenous variables. In general, it can be written like this:

$$y_{2t} = b_{21}y_{1t} + b_{23}y_{3t} + ... + b_{2m}y_{mt} + c_{21}x_{1t} + c_{22}x_{2t} + ... + c_{2k}x_{kt} + u_{2t},$$

$$y_{2t} = b_{21}y_{1t} + b_{23}y_{3t} + ... + b_{2m}y_{mt} + c_{21}x_{1t} + c_{22}x_{2t} + ... + c_{2k}x_{kt} + u_{2t}, ...,$$

$$y_{mt} = b_{m1}y_{1t} + b_{m2}y_{2t} + ... + b_{mm-1}y_{m-1t} + c_{m1}x_{1t} + c_{m2}x_{2t} + ... + c_{mk}x_{kt} + u_{mt}.$$

Certain macroeconomic models built with a system of simultaneous equations can be a powerful econometric tool as a result, which will make it possible to investigate complex relationships in various kinds of socio-economic systems, in particular, relationships in ecological-socio-economic systems, in conditions of certain uncertainty, high risks and rapid changes in the economic environment.

Simultaneous models can be both quite detailed and quite compact, so they can be used not only for in-depth analysis considering various scenarios of system development, but also for preliminary diagnosis of the system state or display of the behavior of certain of its components in different situations.

Structural equations are used for sustainable development modeling in the investigations of urbanisation [42], green buildings [43], business environment [44], machine-building enterprises [45] and others.

For modeling sustainable development, simultaneous models can also be considered quite effective, as they make it possible to analyze and forecast the development of environmental, social and economic components both separately and to consider their interrelationships. Also, such modeling makes it possible to assess the overall impact on sustainable development of the changes implemented in each of its components and, if necessary, to change the further strategy.

3. Structural model of sustainable development of Ukraine on three-pillar approach

A simultaneous model of three equations, each of which describes one of the three components of sustainable development (ecological, economic, and social) is proposed for investigation and forecasting the sustainable development of Ukraine.

To describe the economic component, we will use the following variables:

1) Endogenous variable – gross domestic product (million UAH), y_1.
2) Exogenous variables:
   - turnover of retail trade, million UAH, x_1;
   - export of goods, thousands of dollars USA, x_2;
   - inflation, percent, x_3.

To describe the social component:

1) Endogenous variable – disposable income per household, UAH, y_2.
2) Exogenous variables:
   - number of employed population, thousands of people, x_4;
   - average monthly (real) salary per employee, UAH, x_5.

To describe the ecological component:

1) Endogenous variable – expenses for the protection of the natural environment, thousand UAH, y_3.
2) Exogenous variables:
   - volume of emissions of polluting substances into the air by stationary sources, thousand tons, x_6;
   - capital investments for the protection of the natural environment, UAH, x_7.

In general terms, the model looks like this:

$$y_{1t} = f(y_{2t}, y_{3t}, x_{1t}, x_{2t}, x_{3t}, x_{5t}), \tag{1}$$

$$y_{2t} = f(y_{1t}, x_{4t}, x_{5t}), \tag{2}$$

$$y_{3t} = f(y_{1t}, x_{6t}, x_{7t}). \tag{3}$$

The dependence equations will have the following form:

1. Gross domestic product depends on available income per person, costs for environmental protection, retail trade turnover, export of goods, consumer price index, average monthly real wages:

$$y_{1t} = a_{12}y_{2t} + a_{13}y_{3t} + b_{10} + b_{11}x_{1t} + b_{12}x_{2t} + b_{13}x_{3t} + b15x_{5t} + e_{1t}. \tag{4}$$

2. The disposable income per household depends on the gross domestic product, the number of employed people, and the average monthly real wage:

$$y_{2t} = a_{21}y_{1t} + b_{20} + b_{24}x_{4t} + b_{25}x_{5t} + e_{2t}. \tag{5}$$

3. Costs for environmental protection depend on the gross domestic product, the amount of pollutants emitted into the air by stationary sources, capital investments for environmental protection:

$$y_{3t} = a_{31}y_{1t} + b_{30} + b_{36}x_{6t} + b_{37}x_{7t} + e_{3t}. \tag{6}$$

So, the simultaneous model will look like this:

$$y_{1t} = a_{12}y_{2t} + a_{13}y_{3t} + b_{10} + b_{11}x_{1t} + b_{12}x_{2t} + b_{13}x_{3t} + b15x_{5t} + e_{1t}, \tag{7}$$

$$y_{2t} = a_{21}y_{1t} + b_{20} + b_{24}x_{4t} + b_{25}x_{5t} + e_{2t}, \tag{8}$$

$$y_{3t} = a_{31}y_{1t} + b_{30} + b_{36}x_{6t} + b_{37}x_{7t} + e_{3t}. \tag{9}$$

Let's check whether the model is identified, for this we will first write it down in tabular form (table 2).

Table 2. Tabular form of the simultaneous model.

y_1	y_2	y_3	x_1	x_2	x_3	x_4	x_5	x_6	x_7
1	$-a_{12}$	$-a_{13}$	$-b_{11}$	$-b_{12}$	$-b_{13}$	0	$-b_{15}$	0	0
$-a_{21}$	1	0	0	0	0	$-b_{24}$	$-b_{25}$	0	0
$-a_{31}$	1	0	0	0	0	0	0	$-b_{36}$	$-b_{37}$

Let us now check the order condition and rank condition for each equation of the constructed simultaneous model (table 3).

Table 3. Order condition and rank condition.

Equation №	Not included variables	Matrix rank	Included variables-1	Conclusion
1	4	2	2	over identified
2	5	2	2	over identified
3	4	2	2	over identified

Since the order and rank conditions are fulfilled for all equations of the model, we conclude that all of them are over identified, and therefore the model as a whole can be considered as over identified.

Since the equations of the model are over- identified, we cannot use the least-squares method to estimate the parameters, that's is why we used the two- step least-squares method. We will estimate the parameters based on the statistical data of the described variables from 2000 to 2020, which were collected from the website of the State Statistics Service of Ukraine.

4. Simultaneous equations of Ukrainian sustainable development

All the input data about exogenous and endogenous variables are collected from the official web-page of the State Statistics Service of Ukraine [46] for the period 2000-2020 years.

The first step is to construct three regression models of the dependence of each endogenous variable on all exogenous variables.

After the actions taken, we have three models for calculating the theoretical values of endogenous variables, which will be used in the second step as auxiliary variables to obtain estimates of the parameters of simultaneous model:

1) for gross domestic product:

$$y_{1t} = 4554526.41 - 1.55x_{1t} + 14.63x_{2t} - 1098.17x_{3t} + 249.03x_{4t} + 372.47x_{5t} + 86.64x_{6t} - 0.009x_{7t}.$$

2) for disposable income per household:

$$y_{2t} = -1707.95 + 0.001x_{1t} + 0.09x_{2t} + 2.32x_{3t} + 0.07x_{4t} + 0.94x_{5t} + 0.014x_{6t} + 0.00007x_{7t}.$$

3) for environmental protection expenses:

$$y_{3t} = 19684709.17 + 10.89x_{1t} + 45.05x_{2t} - 18399.35x_{3t} - 942.65x_{4t} + 791.26x_{5t} + 431.37x_{6t} + 0.28x_{7t}.$$

The three equations have high coefficients of determination, which indicates that the obtained equations of the simultaneous model perfectly explain the variance of the endogenous variables. For the equation of the economic component, this indicator is 99.58 percent, for the equation of the social component – 99.57 percent, and for the equation of the ecological component – 98.96 percent.

We will also check the statistical significance of model parameter estimates. As mentioned earlier, we will do this using the Student's test with a confidence probability of 90 percent.

Tabular values of the Student's criterion at a probability of 0.1 and 14 degrees of freedom is 1.761, and at 17 degrees of freedom – 1.739.

The obtained empirical values of the Student's test were also calculated as a proportion of the obtained variable parameters and their standard error. The results are described in table 4.

Table 4. Empirical and critical values of Student's criterion.

№	y_1	y_2	y_3	x_1	x_2	x_3	x_4	x_5	x_6	x_7	t_{kr}
1	-2.280	-2.335	3.855	-2.069	2.696	1.773	-	2.999	-	-	1.761
2	3.794	-2.411	-	-	-	-	2.581	2.538	-	-	1.740
3	8.276	-	1.748	-	-	-	-	-	2.643	4.681	1.740

Since the empirical values are greater than the critical values, we can reject the null hypothesis and conclude that all parameters of the obtained simultaneous model of sustainable development of Ukraine are statistically significant. That is, we can use the model to further build a forecast.

In the final form, we have the following simultaneous model of sustainable development of Ukraine:

$$y_{1t} = -792974.45 - 922.97y_{2t} + 0.19y_{3t} - 2.74x_{1t} + 14.97x_{2t} + 4488.29x_{3t} + 1081.49x_{5t},$$

$$y_{2t} = -3422.58 + 0.002y_{1t} + 0.17x_{4t} + 0.44x_{5t},$$

$$y_{3t} = -38700954.51 + 4.56y_{1t} + 820.28x_{6t} + 0.69x_{7t}.$$

5. Forecasting three-pillar approach indicators of sustainable development

Based on the model, we will forecast the dynamics of each selected component of Ukraine's sustainable development. We will use the data for 2021, which is on the website of the State Statistics Office of Ukraine [46], as well as their forecasts of the development of some indicators.

First, let's calculate the theoretical values of all our endogenous variables for 2021. As a result, we have that the GDP is UAH 6433133.192 million; available income per household – UAH 13,518.51, expenses for environmental protection – UAH 2,276,465.42 thousand.

Next, we substitute all these values and get that in 2021 GDP will be UAH 6,433,133.192 million, disposable income per household is UAH 17,381.18,027, and costs for environmental protection are UAH 3,872,110.64 thousand.

Figures 1-3 show the dynamics of our selected endogenous variables from 2000 to 2020, the obtained forecast for 2021, as well as the forecast of the State Administration of Statistics of Ukraine and Forecast.

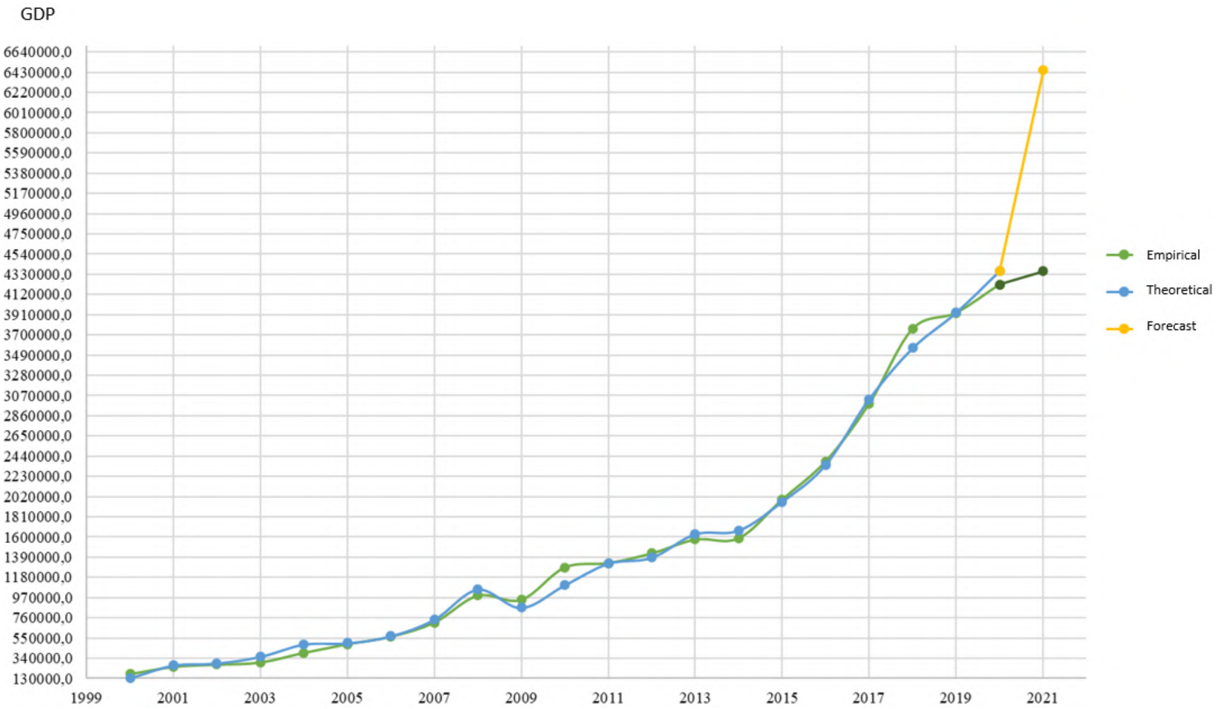

Figure 1. Dynamics and forecast of the gross domestic product.

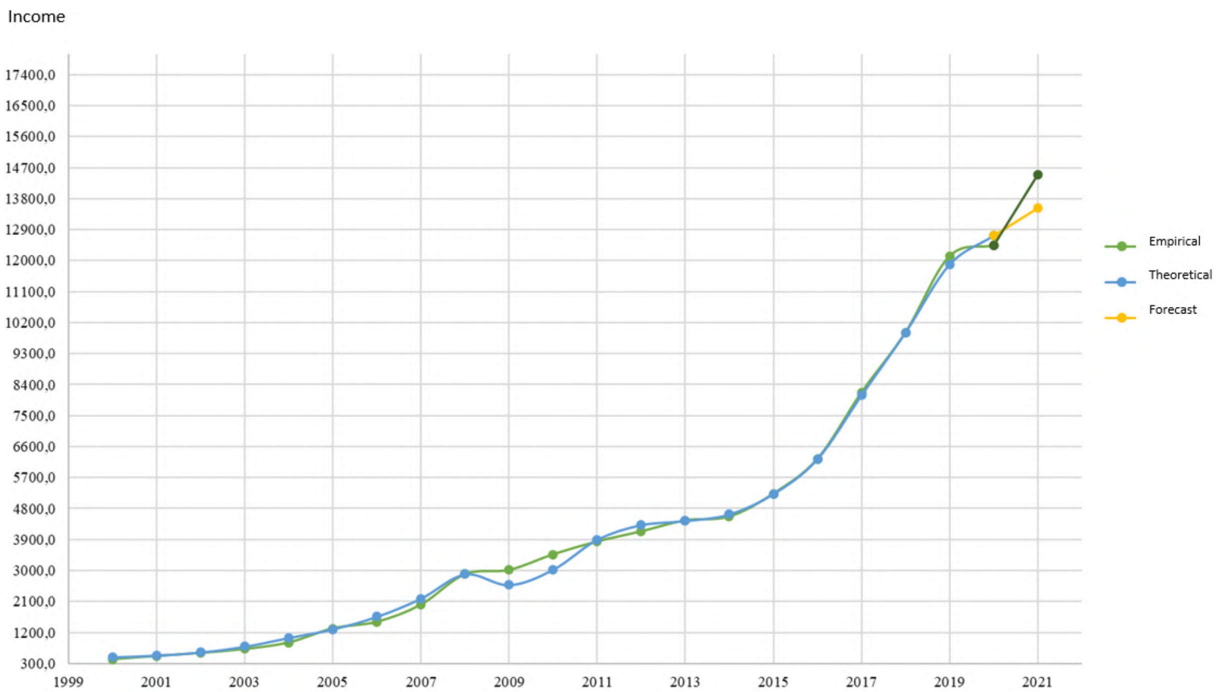

Figure 2. Dynamics and forecast of disposable income per household.

From figures 1-3, it is clear that the forecast for the dynamics of GDP and costs for the protection of the natural environment, which we obtained on the basis of a simultaneous model, significantly exceeds the forecast of the State Statistics Office of Ukraine, but the forecast for

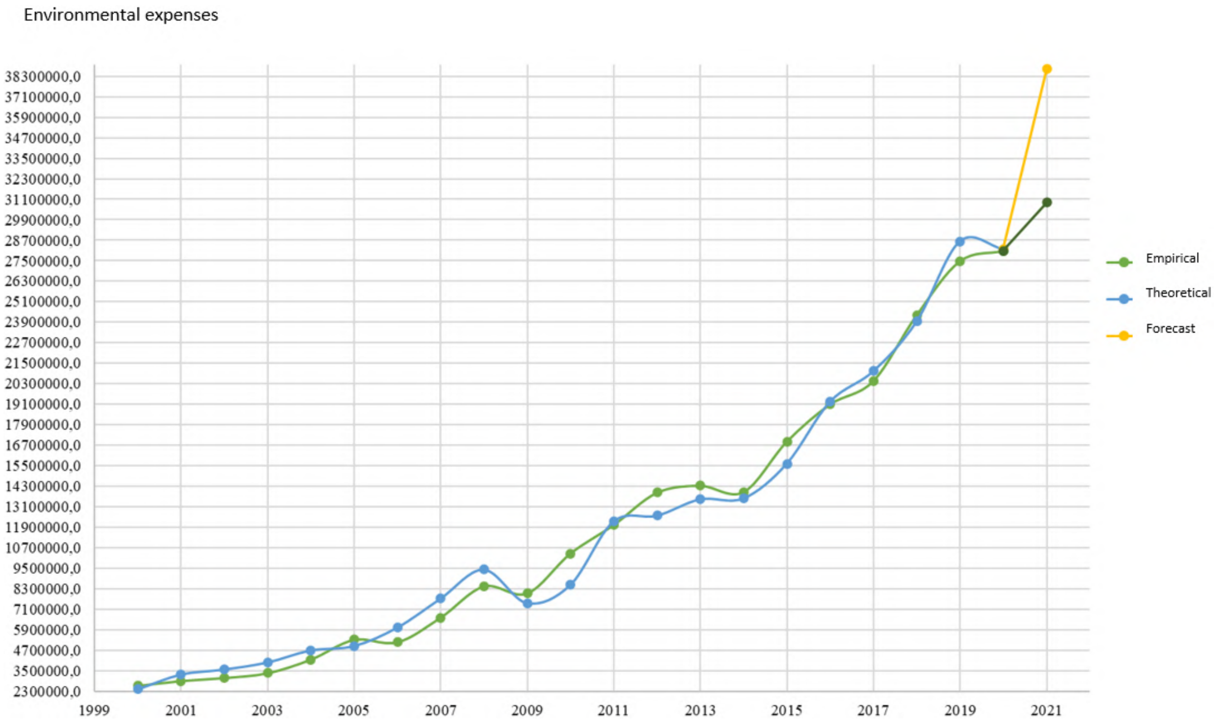

Figure 3. Dynamics and forecast of the expenses for the environment protection.

the change in the dynamics of disposable income per household, on the contrary, shows a less rapid its growth. But in general, both forecasts show a positive development of all indicators.

6. Conclusions

The proposed and implemented structural model of sustainable development of Ukraine based on the three-pillar approach. The economic component of development is represented by GDP as a function of wages, trade turnover, exports and inflation. The social component is described in terms of income per person as a function of GDP, average wages and the number of employed population. Environmental protection costs, which depend on GDP, emissions from stationary sources of pollution, etc., and capital investments in the environment, were used as an ecological characteristic. Since GDP is both the dependent variable in the first equation and the independent variable in the next two equations, the interaction between the three pillars of sustainable development can be explored. In this way, it was found that the growth of household income is not accompanied by the growth of GDP, that is, incomes grow faster than the economy, which is quite unexpected. Simultaneously with the growth of the GDP of Ukraine, the income of households increases, which can be seen from the equation that describes the social component. If we talk about the environmental component, the growth of environmental protection costs is accompanied by GDP growth, and vice versa, GDP growth increases environmental protection costs. Forecasts of three exogenous variables were also obtained, which differs from the official forecasts, but also confirmed the correct selection of variables and the description of the dependencies between them.

Unfortunately, the State Statistics Service has suspended the publication of statistical information for the period of martial law or the state of war, as well as for three months after its termination, and for the occupied territories, even the collection of statistics is not possible. It is obvious that with the beginning of a full-scale invasion, statistical economic, social and environmental indicators have undergone catastrophic changes (which have not yet acquired a clear quantitative dimension) and the assessment of the scale of losses is still ahead. Catastrophic changes took place in various areas, including those that describe the social, economic and ecological components of sustainable development, goals and priorities changed dramatically, so the correctness of forecasts for the following periods will require additional clarification.

The deepest decline of the Ukrainian economy in the entire history of the state took place, household incomes experienced a significant reduction and often large changes in the structure, the environmental consequences of the war also cause significant concern. Obviously, the classical econometric model could not take into account such changes, but it allows to investigate the structure of dependencies between economic, social and environmental indicators and provides tools for its explanation.

We also note that the reconstruction of Ukraine will take place on the basis of the concept of sustainable development and require adequate justification of decisions, and econometric approaches can be used for this purpose.

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References

[1] United Nations 2015 Transforming our World: The 2030 Agenda for Sustainable Development URL https://sustainabledevelopment.un.org/content/documents/21252030%20Agenda%20for%20Sustainable%20Development%20web.pdf
[2] 2021 Sustainable Development Goals Voluntary National Review: Ukraine URL https://ukraine.un.org/en/151096-sustainable-development-goals-voluntary-national-review-ukraine
[3] Brundtland G H 1987 *Environmental Conservation* **14**(4) 291–294 URL https://doi.org/10.1017/S0376892900016805
[4] Beckerman W 1994 *Environmental Values* **3**(3) 191–209 URL https://doi.org/10.3197/096327194776679700
[5] Salvia A L, Leal Filho W, Brandli L L and Griebeler J S 2019 *Journal of Cleaner Production* **208** 841–849 ISSN 0959-6526 URL https://doi.org/10.1016/j.jclepro.2018.09.242
[6] Chabay I 2020 *Evolutionary and Institutional Economics Review* **17**(1) 151–165 ISSN 2188-2096 URL https://doi.org/10.1007/s40844-019-00151-3
[7] Schoenmaker D and Stegeman H 2023 *De Economist* **171**(1) 25–49 ISSN 1572-9982 URL https://doi.org/10.1007/s10645-022-09416-6
[8] Vavoura C and Vavouras I 2022 *Evolutionary and Institutional Economics Review* **19**(1) 449–467 ISSN 2188-2096 URL https://doi.org/10.1007/s40844-021-00217-1
[9] Kastrinos N and Weber K M 2020 *Technological Forecasting and Social Change* **157** 120056 ISSN 0040-1625 URL https://doi.org/10.1016/j.techfore.2020.120056
[10] Koch F and Krellenberg K 2018 *ISPRS International Journal of Geo-Information* **7**(12) 464 URL https://doi.org/10.3390/ijgi7120464
[11] Paolotti L, Del Campo Gomis F J, Agullo Torres A M, Massei G and Boggia A 2019 *Environmental Science & Policy* **92** 207–219 ISSN 1462-9011 URL https://doi.org/10.1016/j.envsci.2018.11.022
[12] Shi Y, Ge X, Yuan X, Wang Q, Kellett J, Li F and Ba K 2019 *Sustainability* **11**(7) 2183 URL https://doi.org/10.3390/su11072183
[13] Gabdrakhmanov N, Rubtzov V, Mustafin M and Pratchenko O 2014 *Mediterranean Journal of Social Sciences* **5**(24) 393 URL http://dx.doi.org/10.5901/mjss.2014.v5n24p393
[14] Polova A, Maksyshko N and Vasylieva O 2021 *E3S Web of Conferences* **280** 04008 URL https://doi.org/10.1051/e3sconf/202128004008
[15] Dasanayaka C H, Murphy D F, Nagirikandalage P and Abeykoon C 2021 *Cleaner Environmental Systems* **3** 100064 ISSN 2666-7894 URL https://doi.org/10.1016/j.cesys.2021.100064
[16] Garbie I H 2014 *International Journal of Production Research* **52**(16) 4876–4915 URL https://doi.org/10.1080/00207543.2014.893066
[17] Zelinska H, Andrusiv U, Daliak N, Dovgal O and Lagodiienko V 2021 *Journal of Environmental Management and Tourism* **12**(5) 1179–1187 ISSN 2068-7729 URL https://doi.org/10.14505//jemt.v12.5(53).03
[18] Babenko V, Perevozova I, Kravchenko M, Krutko M and Babenko D 2020 *E3S Web of Conferences* **166** 12001 URL https://doi.org/10.1051/e3sconf/202016612001

[19] Kuzior A, Pidorycheva I, Liashenko V, Shevtsova H and Shvets N 2022 *Sustainability* **14**(14) 8487 URL https://doi.org/10.3390/su14148487
[20] Sokil O, Podolchak N, Kniaz S, Sokil Y and Kucher L 2022 *Journal of Environmental Management and Tourism* **13**(7) 1901–1910 ISSN 2068-7729 URL https://doi.org/10.14505/jemt.v13.7(63).10
[21] Semenenko I, Halhash R and Sieriebriak K 2019 *Equilibrium. Quarterly Journal of Economics and Economic Policy* **14**(2) 317–339 URL https://doi.org/10.24136/eq.2019.015
[22] Mykhailova L, Stoyanets N, Mykhailov A, Kharchenko T and Bachev H 2018 *Problems and Perspectives in Management* **16**(3) 28–39 URL https://doi.org/10.21511/ppm.16(3).2018.03
[23] Hens L, Melnyk L H, Matsenko O M, Chyhryn O Y and Gonzales C C 2019 *Marketing and Management of Innovations* **3** 272–284 URL https://doi.org/10.21272/mmi.2019.3-21
[24] Savitska S, Zaika S, Svystun L, Koval L and Haibura Y 2020 *Independent Journal of Management & Production* **11**(8) 571–586 URL https://doi.org/10.14807/ijmp.v11i8.1218
[25] Taghvaee V M, Nodehi M, Arani A A, Jafari Y and Shirazi J K 2023 *Asia-Pacific Journal of Regional Science* **7**(2) 329–353 ISSN 2509-7954 URL https://doi.org/10.1007/s41685-022-00231-0
[26] Udemba E N and Keleş N İ 2022 *Asia-Pacific Journal of Regional Science* **6**(1) 191–212 ISSN 2509-7954 URL https://doi.org/10.1007/s41685-021-00214-7
[27] Liu Z, Li Y and Lin Y 2022 Research on Forest Sustainable Development Intelligent Information Management System Based on ARIMA and MDP *2022 IEEE 2nd International Conference on Data Science and Computer Application (ICDSCA)* pp 1289–1292 URL https://doi.org/10.1109/ICDSCA56264.2022.9988122
[28] de Armas J, Ramalhinho H, Lalla-Ruiz E, Melian-Batista B and Moreno-Vega M 2019 *Journal of Advanced Transportation* **2019** 4146362 ISSN 0197-6729 URL https://doi.org/10.1155/2019/4146362
[29] Wu Q, Zheng H, Guo X and Liu G 2022 *Renewable Energy* **199** 977–992 ISSN 0960-1481 URL https://doi.org/10.1016/j.renene.2022.09.036
[30] Chai J, Wang Y, Wang S and Wang Y 2019 *Journal of Cleaner Production* **229** 775–786 ISSN 0959-6526 URL https://doi.org/10.1016/j.jclepro.2019.04.393
[31] Moreta G, Loza-Aguirre E, Armas C M and Flores D A 2021 Evaluating Social and Ecological Sustainability Initiatives in Global Companies Using Text Analysis Techniques *2021 Fifth World Conference on Smart Trends in Systems Security and Sustainability (WorldS4)* pp 254–259 URL https://doi.org/10.1109/WorldS451998.2021.9514049
[32] Zomchak L and Starchevska I 2023 Macroeconomic Determinants of Economic Development and Growth in Ukraine: Logistic Regression Analysis *Advances in Intelligent Systems, Computer Science and Digital Economics IV* ed Hu Z, Wang Y and He M (Cham: Springer Nature Switzerland) pp 358–368 ISBN 978-3-031-24475-9 URL https://doi.org/10.1007/978-3-031-24475-9_31
[33] Holloway J and Mengersen K 2018 *Remote Sensing* **10**(9) 1365 URL https://doi.org/10.3390/rs10091365
[34] Alharbi Y, Arribas-Be D and Coenen F 2019 Sustainable Development Goal Attainment Prediction: A Hierarchical Framework using Time Series Modelling *Proceedings of the 11th International Joint Conference on Knowledge Discovery, Knowledge Engineering and Knowledge Management (IC3K 2019) - KDIR* INSTICC (SciTePress) pp 297–304 ISBN 978-989-758-382-7 ISSN 2184-3228 URL https://doi.org/10.5220/0008067202970304
[35] Bielinskyi A, Semerikov S, Serdyuk O, Solovieva V, Soloviev V N and Pichl L 2020 Econophysics of sustainability indices *Proceedings of the Selected Papers of the Special Edition of International Conference on Monitoring, Modeling & Management of Emergent Economy (M3E2-MLPEED 2020), Odessa, Ukraine, July 13-18, 2020* (*CEUR Workshop Proceedings* vol 2713) ed Kiv A (CEUR-WS.org) pp 372–392 URL https://ceur-ws.org/Vol-2713/paper41.pdf
[36] Chen L, Wang Y, Lai F and Feng F 2017 *Journal of Cleaner Production* **142** 1638–1649 ISSN 0959-6526 URL https://doi.org/10.1016/j.jclepro.2016.11.129
[37] Sutthichaimethee P and Ariyasajjakorn D 2021 *International Journal of Energy Economics and Policy* **11**(5) 472–482 URL https://doi.org/10.32479/ijeep.9995
[38] Izonin I, Greguš ml M, Tkachenko R, Logoyda M, Mishchuk O and Kynash Y 2019 SGD-Based Wiener Polynomial Approximation for Missing Data Recovery in Air Pollution Monitoring Dataset *Advances in Computational Intelligence* ed Rojas I, Joya G and Catala A (Cham: Springer International Publishing) pp 781–793 ISBN 978-3-030-20521-8 URL https://doi.org/10.1007/978-3-030-20521-8_64
[39] Horoshkova L, Khlobystov I, Kozmenko S and Trofymchuk V 2020 *International Journal of Global Environmental Issues* **19**(1-3) 143–157 URL https://www.inderscienceonline.com/doi/abs/10.1504/IJGENVI.2020.114870
[40] Matviychuk A, Novoseletskyy O, Vashchaiev S, Velykoivanenko H and Zubenko I 2019 *SHS Web of Conferences* **65** 06005 URL https://doi.org/10.1051/shsconf/20196506005
[41] Valaskova K, Kliestik T, Svabova L and Adamko P 2018 *Sustainability* **10**(7) 2144 URL https://doi.org/

10.3390/su10072144
[42] Jiao L, Shen L, Shuai C and He B 2016 *Sustainability* **8**(9) 910 URL https://doi.org/10.3390/su8090910
[43] Teng J, Mu X, Wang W, Xu C and Liu W 2019 *Sustainable Cities and Society* **44** 215–226 ISSN 2210-6707 URL https://doi.org/10.1016/j.scs.2018.09.038
[44] Brychko M, Bilan Y, Lyeonov S and Streimikiene D 2023 *Sustainable Development* **31**(2) 587–599 URL https://doi.org/10.1002/sd.2410
[45] Latysheva O, Rovenska V, Smyrnova I, Nitsenko V, Balezentis T and Streimikiene D 2021 *Journal of Enterprise Information Management* **34**(1) 328–342 URL https://doi.org/10.1108/JEIM-12-2019-0419
[46] State Statistics Service of Ukraine URL https://www.ukrstat.gov.ua/

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Modified assessment methodology ESG competitiveness of enterprises to a new generation of investors

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Abstract. The article substantiates the expediency of modifying the methodology for assessing business competitiveness in the context of accelerated global ESG integration. The authors propose a system of criteria for assessing the competitiveness of enterprises, taking into account the requirements of the EU Taxonomy, Regulation (EU) 2020/852, the CSRD, and stakeholder requests for information support for assessing ESG risks and ESG competitiveness of enterprises. This system of criteria is based on a cognitive approach. Thanks to the use of modeling and information tools, it is based on a lateral understanding of the clarity of the distinction between the criteria and sub-criteria for assessing the ESG competitiveness indicator and its components. The introduction of a system of criteria for assessing the competitiveness of enterprises will ensure obtaining realistic results and making informed decisions to strengthen the competitive advantages of enterprises for a new generation of "conscious investors". The author's own methodology for integral assessment of ESG competitiveness of metallurgical enterprises is proposed. This methodology is based on the synthesis of integral and reference approaches to assessing the homeostasis of competitiveness. It is adapted to the information support of the Management Report prepared in accordance with the GRI (Global Reporting Initiative) and SASB (Sustainability Accounting Standards Board) standards. Its peculiarity is the assessment based on the extended homeostatic plateau of the dynamic system for determining the thresholds of the optimality of the ESG competitiveness indicator of enterprises. This should become the basis for ESG rating and the fundamental basis for determining strategic imperatives for managing the competitiveness of enterprises in the context of global ESG integration.

1. Introduction

The aggravation of the triple planetary crisis due to the shortage of natural resources, environmental pollution and climate change requires a transition to a low-carbon economy. Society's expectations are growing and require preserving the planet's sustainability for future generations. In this context, the integration of sustainability and sustainable development (ESG integration) is recognized as one of the strategic priorities of steel companies. When the question of their competitiveness arises, it is about ESG competitiveness.

Traditionally, the competitiveness of enterprises is assessed through a comparative analysis of integrated competitiveness indicators. It is also possible through a comparative analysis of rating indicators or rating positions. In the context of ESG integration, there is a need to revise approaches to assessing the competitiveness of enterprises, that is, to modify the methodology for its assessment [1, p. 66].

2. Literature review

Usually, the competitiveness of enterprises was assessed by financial and economic indicators [2–6]. However, this is not enough in the context of ESG integration. Investors are increasingly considering the social impact of their investments when choosing an investment object and strive to create added value in their investment portfolio for the benefit of future generations [7]. That is why, according to Segal [8], Datsii et al [9], nowadays attention is increasingly focused on the ESG competitiveness of enterprises.

There are still no uniform criteria for its assessment [8, p. 18]. The number of metrics for its assessment offered by analytical centers, rating companies and stock exchanges is growing steadily every year. The metrics proposed by the Global Sustainable Development Goals, RobecoSAM, the Global Reporting Initiative (GRI), EcoVadis 180+, Bloomberg 700+, ISS 300-500, RobecoSAM 600, Sustainalytics 300+, and companies of the DAX, MDAX, SDAX and TechDAX indices on the Frankfurt Stock Exchange (FWB) are currently used in the world practice, The London Stock Exchange (LSE) (which issued guidelines for ESG reporting in response to requests from investors for whom such information is key to their investment decision-making), the Warsaw Stock Exchange (WSE) (which created the WIG-ESG index, which is followed by the NN TFI fund). In May 2020, the European Central Bank issued guidelines for assessing climate and environmental risks for financial institutions, etc. [8, p. 18].

Of particular note is the methodology for assessing ESG competitiveness based on corporate sustainability indicators. It was introduced in Ukrainian practice in 2019 during the first and only professional rating assessment Sustainable Ukraine (based on the DJSI approach). This was carried out as part of a global international project on ESG rating of CIS countries and enterprises with the strategic support of Standard & Poor's Financial Services LLC, S&P Global (owner of the world's most authoritative SR/ESG rating – Dow Jones Sustainability Raitng/index). The aim of the project was to present to the international investment community a holistic picture of Ukraine's corporate sector in terms of sustainable development and corporate social responsibility [10].

Scientists have their own opinions on this matter. Thus, Datsii et al [9, p. 67] argue that in the world and domestic practice there is no single methodology for scoring (assessing) the ESG direction of business. For the first time, the author's model of scoring trends and regularities of business development is proposed in accordance with ESG-principles, in contrast to traditional trend dynamic models, which identifies and iteratively conceptualizes processes by the set of ESG-indicator components determined using the cocoupling-analysis toolkit (tools for assessing the cocoupling-effect).

There are many examples of metrics for assessing the ESG competitiveness of enterprises. Each of them has advantages and disadvantages. The main disadvantage is that when assessing the ESG competitiveness of enterprises, we believe that the limits of its optimality are ignored. This is usually of the greatest interest to investors and stakeholders in obtaining the expected effects (environmental, social and corporate governance). Any deviation from the defined limits of optimality is accompanied by ESG risks and certain losses. Taking into account the shortcomings of the methods for assessing the ESG competitiveness of enterprises, we consider it appropriate to propose our own methodology for assessing the ESG competitiveness of metallurgical enterprises. This methodology is based on a symbiosis of the integral and benchmark approaches.

3. Calculation methodology

The ESG competitiveness of an enterprise is characterized by a set of numerous indicators. These indicators have been prioritized by each of the components of ESG competitiveness (table 1).

Table 1. A set of indicators for assessing the ESG competitiveness of metallurgical enterprises.

No.	Indicators	Measurement units	Abbreviations
	Partial indicators of the E-component of the ESG indicator		
1	Investments in environmental protection	mln USD	E_1
2	Gross greenhouse gas emissions in CO2 equivalent per 1 ton of steel	t/ton of steel	E_2
3	Total water intake per 1 ton of steel	m^3/ton of steel	E_3
4	Amount of waste recycled	t/ton of steel	E_4
5	Total energy consumption	GJ/ton of steel	E_5
	Partial indicators of the S-component of the ESG indicator		
6	Investments in occupational health and safety	mln USD	S_1
7	Lost time injury frequency rate	without dimension	S_2
8	Investments in healthcare	mln USD	S_3
9	Investments in local communities	mln USD	S_4
10	Payroll level coefficient	without dimension	S_5
	Partial indicators of the G-component of the ESG indicator		
11	Reporting on impact by taxonomy	mln USD	G_1
12	Investment in sustainable development	mln USD	G_2
13	Income	mln USD	G_3
14	Total debt	mln USD	G_4
15	Number of employees (number of jobs created)	persons	G_5

The defined structure includes 15 indicators. The list of indicators may vary depending on the objectives and depth of the study. These 15 indicators are grouped by each of the components E_5, S_5, G_5. To simplify understanding and demonstration, the results of the modeling [11] are presented in the form of a vector:

$$\overline{R} = \{r_1; r_2; \ldots; r_n\}, \quad (1)$$

n – number of indicators.

With this decision, the question of the unidirectionality of the indicators E_j, S_j, G_j. Because among the indicators identified in table 1, some of them should increase (stimulators) and others should decrease (discouragers) to ensure the ESG competitiveness of enterprises. The unidirectionality of the indicators E_j, S_j, G_j can be achieved through normalization, in particular, by applying the combined method [12, p. 74]. This is a modified method of normalization by the "range of variation", which provides:

- for positive direction indicators:

$$r_i = \frac{x_i}{x_{\max}}, \quad (2)$$

- for negative direction indicators:

$$r_i = \frac{k_{\text{norm}} \;--x_i}{k_{\text{norm}}}, \quad k_{\text{norm}} = x_{\max} + 7\%. \quad (3)$$

The main disadvantage of the combined method of normalization is that the standardized indicators that form the information basis for calculating the generalized and integral ones affect the latter with equal force. Their influence is equilibrium. This is not always justified in practice.

This shortcoming can be neutralized by introducing hierarchy coefficients (weighting). This will divide the indicators E_j, S_j, G_j by their significance, strength of influence on the generalized and integral indicator of ESG competitiveness of enterprises. The question arises of determining the weighting coefficients of indicators for each component of the ESG competitiveness of enterprises. This is possible using one of the approaches presented in table 2.

Table 2. Methods for determining the weighting coefficients of each component of the ESG competitiveness indicator of an enterprise [11, p. 46].

The method	Calculation methodology	Advantages
The method of sensitivity theory	$a_i = \dfrac{\lvert u_i \Delta y_i \rvert}{\sum\limits_{i=1}^{n} \lvert u_i \Delta y_i \rvert}$	allows adjusting the weighting coefficients in each period to make them more relevant to the real economy
The method of principal components	$a_i = \dfrac{c_i \lvert d_i \rvert}{\sum c_i \lvert d_i \rvert}$ c_i – contribution of the i-th component to the total variance of the set of indicators; d_i – factor loads	allows to identify only an averaged pattern, but does not provide strict and accurate correspondence in each individual case (period)
Gaming methods	$I_d = \sum\limits_{j=1}^{n} (S_{2j}^{*}) z_{j,t}$ $I_m = \prod\limits_{j=1}^{n} z_{j,t}^{(s_{2j})}$	characterizes the set of weighting coefficients required to form the indicator in additive or multiplicative form

Determination of the indicator of ESG competitiveness of enterprises by the method of integral assessment makes it possible to observe changes in this indicator in the dynamics and to carry out a multicriteria analysis of the competitiveness of enterprises. However, this is not enough to make informed management decisions on maintaining the competitive position of enterprises and improving them in the context of accelerated competition.

For a more realistic assessment of the ESG competitiveness indicator of enterprises and the possibility of forecasting its changes in the medium and long term, we consider it advisable to apply a methodology based on the synthesis of integral and benchmark approaches to assessing business homeostasis. This methodology is adapted to the information support of the Management Report prepared in accordance with the GRI (Global Reporting Initiative) and SASB (Sustainability Accounting Standards Board) standards. It provides for the assessment of the extended homeostatic plateau of the dynamic system for determining the thresholds for the optimality of the ESG competitiveness indicator of enterprises and its components. This can become the basis for ESG rating and the fundamental basis for determining strategic imperatives for managing the competitiveness of enterprises in the context of accelerated global ESG integration. That is why, for each of the components E_j, S_j, G_j of the competitiveness of enterprises, it is necessary to determine the vector of threshold values, namely: lower critical ($x_{\text{low\_k}}$); lower threshold ($x_{\text{low\_lim}}$); lower optimal ($x_{\text{low\_opt}}$); upper optimal ($x_{\text{h\_opt}}$); upper threshold ($x_{\text{h\_lim}}$); upper critical ($x_{\text{h\_k}}$) [13, p. 52].

There is a fairly large number of methods for determining the threshold vector. The most adequate, from our point of view, for this task is the stochastic method of the t-criterion. According to this method, probability density functions should be constructed for given samples of statistical data of competitiveness indicators and statistical characteristics should be calculated: mathematical expectation, standard deviation and coefficient of asymmetry [14, p. 22].

Based on the results of the analysis of statistical data, it was found that the competitiveness indicators assume the hypotheses of normal and exponential distributions. They include formulas for calculating the vector of threshold values [12, p. 70–72], [14, p. 29]:

$$x_{\text{low\_k}} = \mu \;-\; -3 \cdot \sigma, \quad x_{\text{low\_lim}} = \mu \;-\; -t \cdot \sigma, \quad x_{\text{low\_opt}} = \mu \;-\; -\sigma \tag{4}$$

$$x_{\text{h\_opt}} = \mu + \sigma, \quad x_{\text{h\_lim}} = \mu + t \cdot \sigma, \quad x_{\text{h\_k}} = \mu + 3 \cdot \sigma \tag{5}$$

for the exponential law (tail to the right)

$$x_{\text{low\_k}} = \mu \;-\; -\frac{3 \cdot \sigma}{k_{\text{as}}}, \quad x_{\text{low\_lim}} = \mu \;-\; -\frac{\sigma}{k_{\text{as}}}, \quad x_{\text{low\_opt}} = \mu, \tag{6}$$

$$x_{\text{h\_opt}} = \mu + \sigma, \quad x_{\text{h\_lim}} = \mu + t \cdot \sigma, \quad x_{\text{h\_k}} = \mu + 3 \cdot \sigma, \tag{7}$$

for the exponential law (tail to the left)

$$x_{\text{low\_k}} = \mu \;-\; -3 \cdot \sigma, \quad x_{\text{low\_lim}} = \mu \;-\; -t \cdot \sigma, \quad x_{\text{low\_opt}} = \mu \;-\; -\sigma, \tag{8}$$

$$x_{\text{h\_opt}} = \mu, \quad x_{\text{h\_lim}} = \mu + \frac{\sigma}{k_{\text{as}}}, \quad x_{\text{h\_k}} = \mu + \frac{3 \cdot \sigma}{k_{\text{as}}}, \tag{9}$$

t – Student's criterion;
μ – mathematical expectation;
σ – standard deviation;
k_{as} – coefficient of asymmetry.

Establishing thresholds can help build a simulation model of optimal business immunity (homeostasis). To do this, it is necessary to identify:

I – zone of low ESG competitiveness;
II – zone of conditionally acceptable ESG competitiveness (low);
III – zone of optimal ESG competitiveness;
IV – zone of conditionally acceptable ESG competitiveness (high);
V – zone of critical ESG competitiveness.

Under conditions of variability and uncertainty, the limits of optimality of ESG competitiveness and threshold values of the I_E, I_S, I_G indicators may change under the influence of both endogenous and exogenous factors [15, p. 43]. Indicators of immunity (homeostasis) of ESG competitiveness of enterprises are indicators of statics. However, for management decision-making and strategizing, dynamics indicators are currently more important, as they make it possible to observe existing trends and see the future. Therefore, when studying the ESG competitiveness of enterprises, an equally important stage as the previous ones is to assess the vulnerability of ESG competitiveness immunity under the influence of ESG risks and threats.

4. Research results

The authors consider it expedient to do this by rating them according to the scale presented in table 3.

Table 3. Scale for assessing the intensity of threats to the ESG competitiveness of metallurgical enterprises from decarbonization pressure.

Level	Category	Average score values	Characterizing the intensity of ESG risks and threats to the competitiveness of enterprises
A	A1.tr	> 0.80-1.00	Absolutely uncontrolled
	A2.tr	> 0.63-0.80	Insufficiently controlled
B	B1.tr	> 0.37-0.63	Conditionally controlled
	B2.tr	> 0.20-0.37	Sufficiently controlled
C	C.tr	0.00-0.20	Absolutely controlled

The choice of values on the scale of 0.63 and 0.37 is due to the convenience of the calculations: $0.63 \approx 1-(1/e)$, $0.37 \approx 1/e$. The value of $di = 0.37$ usually corresponds to the limit of acceptable values.

In accordance with the defined categories of ESG risks and threats, the correction factor k_r should be determined. It should be used to adjust the limits of optimality of ESG competitiveness and thresholds of the I_E, I_S, I_G indicators.

The frequency of reviewing the limits of optimality of ESG competitiveness and the thresholds of the I_E, I_S, I_G indicators (annual, quarterly) should be specified in the standards for assessing and rating the ESG competitiveness of enterprises.

To confirm the viability of the proposed methodology for assessing the ESG competitiveness of enterprises, we applied it to the assessment of the competitiveness of Arcelor Mittal Group enterprises (table 4).

Table 4. Dynamics of the integrated indicator of ESG competitiveness of metallurgical enterprises in 2010-2021 [16–24].

The companies	Years											
	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Arcelor Mittal Kryvyi Rih (Ukraine)	0.25	0.247	0.244	0.241	0.250	0.226	0.183	0.219	0.220	0.219	0.191	0.203
Arcelor Mittal Tubarão (Brazil)	0.302	0.248	0.252	0.274	0.288	0.233	0.247	0.243	0.290	0.320	0.271	0.294
Arcelor Mittal Asturias (Gijon) Spain	0.352	0.341	0.347	0.306	0.318	0.336	0.346	0.372	0.462	0.438	0.421	0.434
Arcelor Mittal Bremen (Germany)	0.357	0.358	0.403	0.433	0.452	0.452	0.478	0.497	0.479	0.485	0.465	0.469
Arcelor Mittal Luxembourg (Luxembourg)	0.214	0.203	0.215	0.235	0.223	0.231	0.222	0.243	0.255	0.248	0.235	0.239
Arcelor Mittal Acindar (Argentina)	0.237	0.239	0.232	0.248	0.239	0.258	0.250	0.262	0.246	0.250	0.238	0.243

The existing methodology for forming information support for assessing ESG competitiveness creates a certain limitation in access to information on compliance with ESG principles by enterprises. To model the level of ESG competitiveness of metallurgical enterprises, a set of indicators sufficient for calculations was selected (based on the availability of reliable information sources) (table 5).

Table 5. A set of indicators for assessing the ESG competitiveness of metallurgical enterprises.

No.	Indicators	Measurement units	Abbreviations	Weighting coefficients
	Partial indicators of the E-component of the ESG indicator			
1	Investments in environmental protection	mln USD	E_1	0.307
2	Gross greenhouse gas emissions in CO2 equivalent per 1 ton of steel	t/ton of steel	E_2	0.323
3	Total water intake per 1 ton of steel	m^3/ton of steel	E_3	0.089
4	Amount of waste recycled	t/ton of steel	E_4	0.116
5	Total energy consumption	GJ/ton of steel	E_5	0.165
	Partial indicators of the S-component of the ESG indicator			
6	Investments in occupational health and safety	mln USD	S_1	0.312
7	Lost time injury frequency rate	without dimension	S_2	0.097
8	Investments in healthcare	mln USD	S_3	0.164
9	Investments in local communities	mln USD	S_4	0.151
10	Payroll level coefficient	without dimension	S_5	0.276
	Partial indicators of the G-component of the ESG indicator			
11	EBITDA	mln USD	G_1	0.319
12	Capital investments	mln USD	G_2	0.295
13	Investments in research and development (R&D)	mln USD	G_3	0.154
14	Investment in education	mln USD	G_4	0.133
15	Average hours of training per employee	h./person.	G_5	0.099

To ensure ESG competitiveness, some indicators should increase (stimulators) and others should decrease (disincentives). The unidirectionality of the indicators E_j, S_j, G_j can be achieved through norming. Therefore, indicators r_i $(i = \overline{1,15})$ should be understood as standardized dimensionless values obtained from the values of E_j, S_j, G_j $(j = \overline{1,5})$.

Since the partial indicators of ESG competitiveness of enterprises have different dimensions, to determine the integral indicators of each of the components E-, S- and G-, we will carry out the procedure of normalizing the indicators E_j, S_j, G_j. For a correct comparison, each of the indicators must be normalized (i.e., reduced to the interval from 0 to 1). 0 corresponds to the worst (unacceptable) values of this indicator, and 1 corresponds to the best (optimal) values of this indicator.

To normalize the indicators, it is necessary to determine the minimum and maximum values. Next, we normalize using a formula, the form of which depends on the nature of the indicator: whether it is a stimulator or, conversely, a discourager of the enterprise's ESG competitiveness.

Stimulators of ESG competitiveness of enterprises are indicators that contribute to positive changes in the competitive position of the enterprise. This leads to an increase in the ESG competitiveness indicator. Destimulators are indicators that contribute to negative changes in the ESG competitiveness of an enterprise.

The integral indicators E, S, G will be calculated, taking into account the values of the weighting coefficients, using the following formulas:

$$I_{E,t} = r_{E1t^{0.307}} \cdot r_{E2t^{0.323}} \cdot r_{E3t^{0.089}} \cdot r_{E4t^{0.116}} \cdot r_{E5t^{0.165}} \tag{10}$$

$$I_{S,t} = r_{S1t^{0.312}} \cdot r_{S2t^{0.097}} \cdot r_{S3t^{0.164}} \cdot r_{S4t^{0.151}} \cdot r_{S5t^{0.276}} \tag{11}$$

$$I_{G,t} = r_{G1t^{0.319}} \cdot r_{G2t^{0.295}} \cdot r_{G3t^{0.154}} \cdot r_{G4t^{0.133}} \cdot r_{G5t^{0.099}} \tag{12}$$

We perform convolutions (10)–(12) for the components E-, S-, G-. Next, it is necessary to simultaneously perform integral convolutions for their thresholds with an offset by the asymmetry coefficient in relation to the number of metallurgical enterprises under consideration. We obtain the dynamics of the E-, S-, G- components of the integral ESG competitiveness index vector compared to the integral thresholds. This makes it possible to assess the level of ESG competitiveness by components E-, S-, G.

To fully assess the level of ESG competitiveness of metallurgical enterprises, we consider it necessary to carry out a comprehensive assessment of the level of competitiveness of a metallurgical enterprise by the module of the vector of the integrated competitiveness indicator. To do this, we need to normalize it using the formula:

$$I_{\mathrm{ESG},t} = \frac{\sqrt{I_{E,t^2} + I_{S,t^2} + I_{G,t^2}}}{I_{\mathrm{ESG,max}}} \tag{13}$$

$I_{\mathrm{ESG,max}} = \sqrt{1^2 + 1^2 + 1^2} = 1{,}732$ is the largest possible value of the vector's modulus, given the values of its components in the interval $[0, 1]$.

Similarly, having calculated the threshold values of the integrated ESG competitiveness indicator, it was found that only Metinvest (Ukraine), ArcelorMittal Bremen (Germany) and, starting from 2017, ArcelorMittal Asturias (Gijon) Spain meet the optimal competitiveness limits of metallurgical enterprises during the period under study. This confirms the correctness of the ESG competitiveness indicators calculations presented in table 4.

Within the framework of the proposed simulation model of the limits of optimality of ESG competitiveness of enterprises (figure 1), it is necessary to establish the compliance of each enterprise with the ESG competitiveness zones.

For the defined thresholds (table 6), the following zones of ESG competitiveness are defined for each of the indicators I_E, I_S, I_G:

I – zone of insufficient ESG competitiveness;
II – zone of conditionally low ESG competitiveness;
III – zone of optimal ESG competitiveness;
IV – zone of conditionally high ESG competitiveness;
V – zone of critical ESG competitiveness.

Table 6. Threshold values of the integrated ESG indicator and its components.

	I_E	I_S	I_G	I_{ESG}
$X_{\mathrm{low\_lim}}$	0.270238	0.261238971	0.225934441	0.253193387
$X_{\mathrm{low\_opt}}$	0.416607	0.424581624	0.396628486	0.412773042
$X_{\mathrm{top\_lim}}$	0.663957	0.682757972	0.704862781	0.684063547
$X_{\mathrm{top\_opt}}$	0.832688	0.846100625	0.875556826	0.851636725

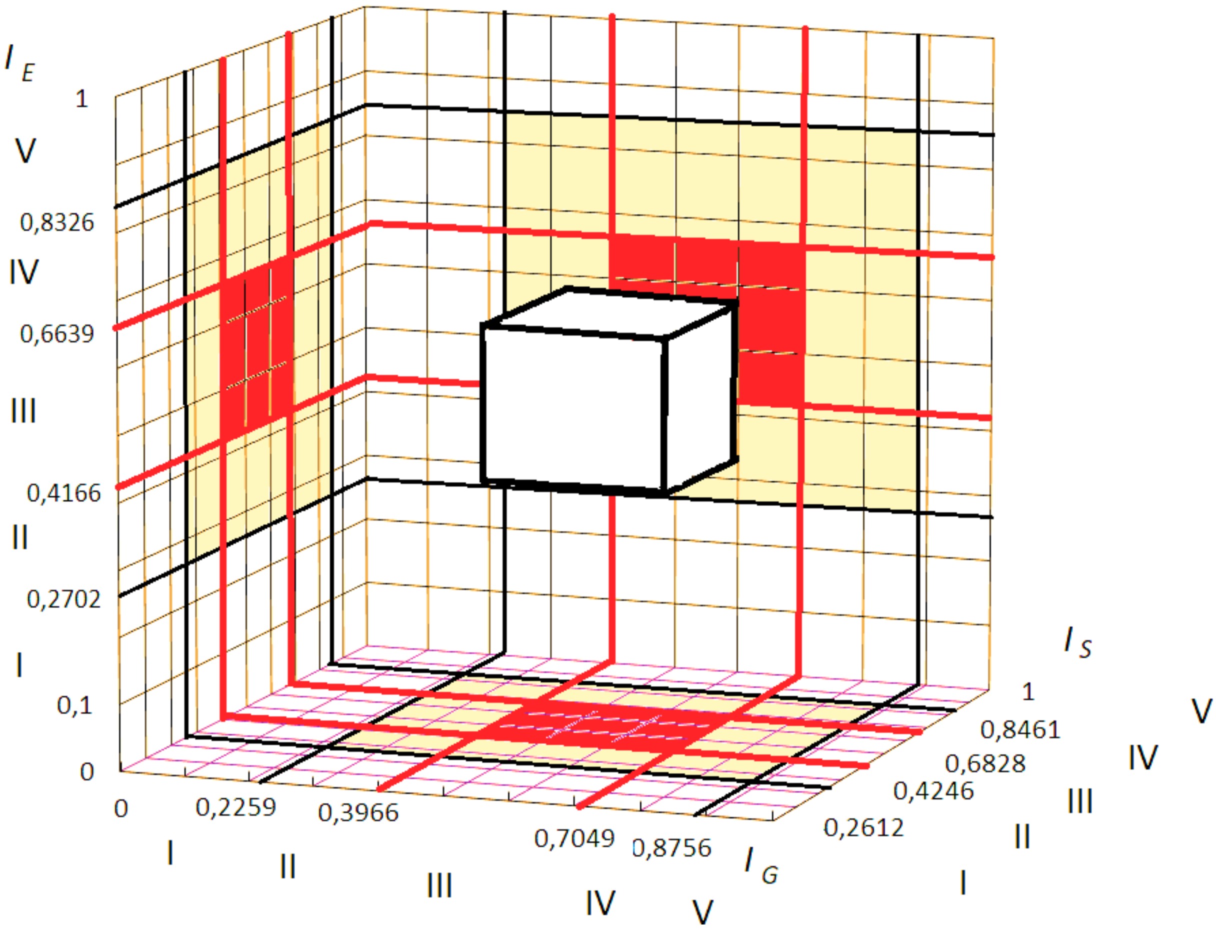

Figure 1. Schematic representation of the threshold zones of the ESG competitiveness indicator of metallurgical enterprises.

Yellow areas correspond to projections of the optimal level of competitiveness. The red areas correspond to the projections of an acceptable level for the integrated ESG competitiveness indicator, I_{ESG}.

Arcelor Mittal Bremen (Germany) and Arcelor Mittal Asturias (Gijon) (Spain) are in the optimal ESG competitiveness zone. This characterizes them as companies with ESG risks that are practically close to zero. Arcelor Mittal Acindar (Argentina), Arcelor Mittal Luxembourg (Luxembourg), and Arcelor Mittal Tubarão (Brazil) are in the zone of conditionally low ESG competitiveness. This confirms that ESG investments can be accompanied by ESG risks.

Only Arcelor Mittal Kryvyi Rih (Ukraine) is in the zone of insufficient (low) ESG competitiveness among the studied metallurgical enterprises. Its ESG investments are the most risky.

The ESG competitiveness of metallurgical enterprises is determined by the amount of invested capital. To assess the forecast of ESG competitiveness, let us find out whether there is a relationship between the ESG competitiveness indicator and total ESG investments. Let's determine the total ESG investments:

$$Q_{E,t} = E_{1,t}, \quad Q_{S,t} = S_{1,t} + S_{3,t} + S_{4,t}, \quad Q_{G,t} = G_{2,t} + G_{3,t} + G_{4,t} \tag{14}$$

It is proposed to use the hyperbolic tangent function for the functional dependence of the integrated ESG competitiveness indicator on total ESG investments. This function has a right

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asymptote of one. The value of the index is also limited to one. Using correlation and regression analysis [15], the authors propose the following model of nonlinear multivariate regression:

$$I_{\mathrm{ESG},t} = 0.680 \cdot \tanh^{0.158}(\tilde{Q}_{E,t}) \cdot \tanh^{0.123}(\tilde{Q}_{S,t}) \cdot \tanh^{0.205}(\tilde{Q}_{G,t}) \tag{15}$$

$\tanh x = \frac{e^{x} \;--e^{-x}}{e^{x}+e^{-x}}$;
$\tilde{Q}_{E,t} = \frac{Q_{E,t}}{Q_{E\max}}$, $\tilde{Q}_{S,t} = \frac{Q_{S,t}}{Q_{S\max}}$, $\tilde{Q}_{G,t} = \frac{Q_{G,t}}{Q_{G\max}}$ are normalized values;
$Q_{E\max} = 479.348$, $Q_{S\max} = 1237.824$, $Q_{G\max} = 1223.112$.

The coefficients of the multivariate nonlinear regression (15) after initial smoothing and linearization by logarithmization were found by the generalized least squares method in matrix form [8]. The value of the coefficient of determination $R2 = 0.7529$ is quite close to one. There is a relationship between the indicator and the selected factors. The Fisher's test, $F = 67.05 > F\mathrm{crit}(0.95; 4; 66) = 2.51$, showed that with a reliability of 95% (significance level), we can assume that the corresponding R^2 are statistically significant. The proposed mathematical model (15) is adequate to the statistical data. It can be used to diagnose ESG competitiveness.

The regression level surfaces of (15) are shown in figure 2.

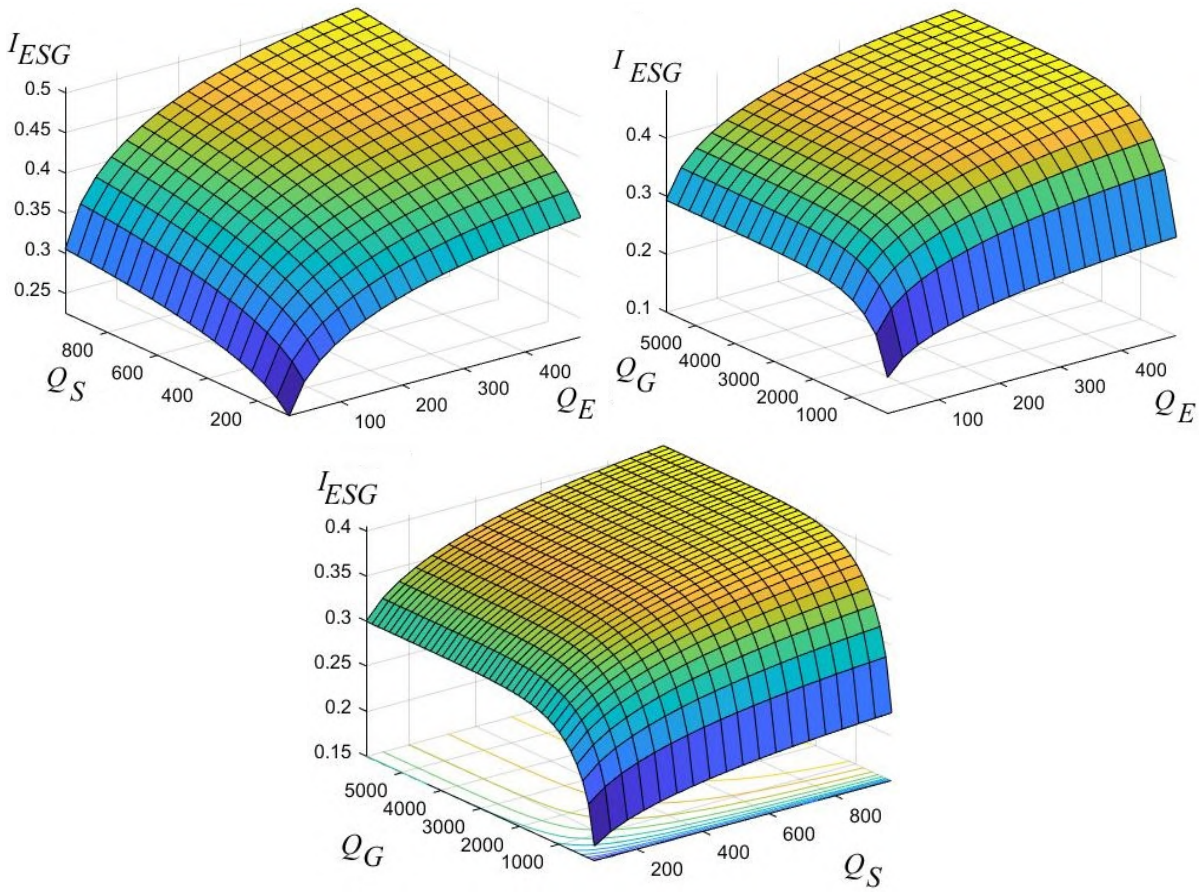

Figure 2. Regression level surfaces of the ESG competitiveness indicator at a fixed value at the level of 2021.

Arcelor Mittal Kryvyi Rih has the lowest level of ESG competitiveness (table 4). We consider the possibility of its improvement if the volume of investments is doubled by 2050 compared to 2021. However, the IESG value does not reach the lower level of the optimality boundary.

According to [13], steel production will remain unchanged in 2050 at the level of 2021, and metallurgical enterprises will need capital investments of 1 thousand USD per ton of steel, i.e. 4,700 million USD.

Table 7. Forecast of the ESG competitiveness indicator of Arcelor Mittal Kryvyi Rih in 2050.

Years	$Q_{E,t}$, mln USD	$Q_{S,t}$, mln USD	$Q_{G,t}$, mln USD	I_{ESG}
Scenario 1 (basic)	50	225	960	0,3539
Scenario 2 (optimistic)	3200	1050	4150	0,4277

Adding this amount to $Q_{G,t}$, then rises above the lower level of the optimality bound I_{ESG}.

It was found that, subject to an increase in ESG investment, Arcelor Mittal Kryvyi Rih will be able to enter the zone of conditionally low ESG competitiveness under the baseline scenario. In the case of the optimistic scenario, the company may get into the zone of optimality.

The threshold values of the limits of optimality of the integrated indicator of ESG competitiveness of metallurgical enterprises and its components E_j, S_j, G_j are determined. This made it possible to form a simulation model of the optimality limits, which should become the fundamental basis for making decisions on ESG investment in metallurgical enterprises.

5. Conclusion

Based on the results of the study, taking into account the requirements of the EU Taxonomy, Regulation (EU) 2020/852, the CSRD, and stakeholder requests for information support for assessing the ESG competitiveness of business, the authors propose a system of criteria for assessing the competitiveness of enterprises. This system is formed according to the cognitive approach, which is based on a lateral understanding of the clarity of the distinction between criteria and sub-criteria for assessing the ESG competitiveness indicator. The implementation of the proposed system in practice will ensure obtaining realistic results, making informed decisions to strengthen the competitive advantages of enterprises in a competitive environment and improving their attractiveness to a new generation of “conscious investors”. The article proposes a methodology for an integrated assessment of the ESG competitiveness of metallurgical enterprises. The methodology is based on the synthesis of integral and reference approaches to assessing the homeostasis of competitiveness. It is adapted to the information support of the Management Report prepared in accordance with the GRI (Global Reporting Initiative) and SASB (Sustainability Accounting Standards Board) standards. Unlike the generally known methods, the methodology provides for the assessment of the extended homeostatic plateau of the dynamic system for determining the thresholds of the optimality of the ESG competitiveness indicator of enterprises and its components. This is the basis of ESG rating and the fundamental basis for determining the strategic imperatives of managing the competitiveness of enterprises in the context of global ESG integration.

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References

[1] Tkachenko A M and Kolesnik E O 2021 *Visnyk Khmelnytskoho natsionalnoho universytetu* (4) 66–72 URL https://doi.org/10.31891/2307-5740-2021-296-4-10
[2] Dereli D 2015 *Procedia - Social and Behavioral Sciences* **195** 1365–1370 URL https://doi.org/10.1016/j.sbspro.2015.06.323
[3] Rugman A M and D'Cruz J R 1993 *MIR: Management International Review* **33** 17–39 ISSN 09388249, 18618901 URL http://www.jstor.org/stable/40228188
[4] 2020 Competitiveness of Enterprises and Small and Medium-sized Enterprises (COSME) URL https://www.efta.int/eea/eu-programmes/cosme
[5] Vijeikis J and Makštutis A 2009 *Ekonomika ir vadyba : aktualijos ir perspektyvos* **2**(15) 328–338 URL https://vb.mruni.eu/object/elaba:6094390/
[6] Yelets O 2016 *Economic Herald of ZDIA* (1) 58–64 URL http://irbis-nbuv.gov.ua/cgi-bin/irbis_nbuv/cgiirbis_64.exe?C21COM=2&I21DBN=UJRN&P21DBN=UJRN&IMAGE_FILE_DOWNLOAD=1&Image_file_name=PDF/evzdia_2016_1_11.pdf
[7] Sokolenko A 2020 Trendy, dosvid, KSV: shcho take naspravdi stalyi rozvytok [Trends, experiences, CSR: What sustainability really means] URL https://mind.ua/ru/openmind/20217286-trendy-opyt-kso-chto-takoe-na-samom-dele-ustojchivoe-razvitie
[8] Segal M 2023 ESG Tied to Stronger Growth and Profitability, Bain and EcoVadis Study Finds URL https://tinyurl.com/3txed5na
[9] Datsii O, Levchenko N, Shyshkanova G, Platonov O and Abuselidze G 3921 *Rural Sustainability Research* **46**(341) 39–52 URL https://doi.org/10.2478/plua-2021-0016
[10] 2019 Sustainable Ukraine – profesiinyi reitynh korporatyvnoi stiikosti ukrainskykh kompanii URL http://web.archive.org/web/20230416012611/https://sustainableukraine.com/ua/index.html
[11] Sukhodolia O M, Kharazishvili Y M, Bobro D H, Smenkovskyi A Y, Riabtsev H L and Zavhorodnia S P 2020 *Enerhetychna bezpeka Ukrainy: metodolohiia systemnoho analizu ta stratehichnoho planuvannia : analit.dop. [Energy security of Ukraine: Methodology of system analysis and strategic planning]* (Kyiv: NISD) URL https://www.researchgate.net/publication/349718527
[12] Kharazishvili Y M 2019 *Systemna bezpeka staloho rozvytku: instrumentarii otsinky, rezervy ta stratehichni stsenarii realizatsii [Systemic Security of Sustainable Development: Assessment Tools, Reserves and Strategic Implementation Scenarios]* (Kyiv) URL https://iie.org.ua/wp-content/uploads/2019/02/Harazishvili_monograf_2019-ost.pdf
[13] Kharazishvily Y M 2014 *Nauka ta naukoznavstvo* 44–58 URL http://nbuv.gov.ua/UJRN/NNZ_2014_4_12
[14] Sukhodolia O, Kharazishvili Y and Bobro D 2020 *Economy of Ukraine* (6) 20–42 URL https://doi.org/10.15407/economyukr.2020.06.020
[15] Kuzmenko O 2014 *Economic and mathematical methods and models (econometrics)* (Sumy)
[16] Mittal L and Mittal A 2019 2018 Financial Results and Strategic Update URL https://storagearcelormittalprod.blob.core.windows.net/media/rm3ojot2/q4-2018-analysts-slides.pdf
[17] Metinvest 2020 Sustainability report 2019 URL https://metinvestholding.com/Content/Entities/Report/26/ua/report-2019.pdf
[18] ArcelorMittal España 2016 Informe de Sostenibilidad 2015 URL https://spain.arcelormittal.com/~/media/Files/A/ArcelorMittal-Espanol/documents/Informe_Sostenibilidad2015_Espana.pdf
[19] ArcelorMittal España 2018 Informe de Sostenibilidad 2017 URL http://web.archive.org/web/20220117044359/https://spain.arcelormittal.com/~/media/Files/A/ArcelorMittal-Espanol/Informe%20DS_2017/InformeSostenibilidadEspana_2017.pdf
[20] ArcelorMittal Tubarão 2020 Relatório de sustentabilidade 2019 URL https://brasil.arcelormittal.com/sala-imprensa/publicacoes-relatorios/brasil/relatorio-de-sustentabilidade-2019
[21] Acindar Grupo ArcelorMittal 2022 Reportes de sustentabilidad URL https://www.acindar.com.ar/reporte-de-sustentabilidad/
[22] ArcelorMittal Luxembourg 2022 Our sustainable development reports URL https://luxembourg.arcelormittal.com/challenges/68/language/EN
[23] ArcelorMittal Luxembourg 2020 Sustainable development report 2020 URL https://luxembourg.arcelormittal.com/repo/reports/2020/Rapport%20D%C3%A9veloppement%20durable%202020_ENG.pdf
[24] ArcelorMittal Acindar 2019 Reporte Integrado 2019 URL https://www.acindar.com.ar/wp-content/uploads/2020/11/Reporte_integrado_Acindar_2019.pdf

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Post-COVID-19 economic recovery in the context of SDG8 and SDG9: the case of selected Eastern European countries

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Post-COVID-19 economic recovery in the context of SDG8 and SDG9: the case of selected Eastern European countries

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Abstract. Assessing the economic development of countries in the context of the tasks defined in the UN 2030 Agenda for Sustainable Development is essential from the point of view of determining progress in achieving the SDGs. It becomes especially relevant in periods of global challenges and disturbances, one of which is the COVID-19 pandemic. The goals of SDG8 and SDG9 contain indicators that are determined mainly by the state of development of the country's economy, so the analysis of trends in their changes is important in the context of identifying trends in economic growth in general, as well as for evaluating progress in achieving these goals. The purpose of the study is to identify the impact of the COVID-19 pandemic on the economic development of countries to achieve sustainable development goals and assess progress trends in the post-pandemic recovery of the economies of Eastern Europe by analyzing quantitative data from official statistical sources. The object of the study is the economic development of Eastern European countries in the conditions of the COVID-19 pandemic. The study period covers the time range from 2017 to 2021 and includes both the pre-pandemic and pandemic periods. Eight countries of Eastern Europe were chosen as research objects. Indicators of official statistics related to SDG8 and SDG9 sub-goals were selected for analysis. The study showed a significant decrease in the values of most indicators, which was caused by the destructive effect of the pandemic. To assess the possible development trajectory, we calculated the estimated value of indicators for 2022 using the Holt-Winters method. The results showed that, despite some progress in 2021, in 2022, the values of the indicators are decreasing. Such estimates correspond to the trends provided by international institutions. We have built a composite indicator to assess the economic development trend comprehensively. The results of the evaluation confirmed the general trend towards a decrease in the level of economic growth in the context of the goals of SDG8 and SDG9 for all the countries of Eastern Europe selected in the study.

1. Introduction

The irrepressible desire to ensure society's economic and technological development was a characteristic feature of the last century. The success of the activity and development of the world's economies was measured mainly by economic indicators, particularly the growth of the gross domestic product. There was a generally accepted opinion in society that this is a sufficient prerequisite for developing well-being and raising the population's standard of living, ensuring the competitiveness of national economies. Achieving appropriate progress was mainly provided due to exploitation and irrational use of natural and resource potential. The results of such irresponsible activity actualized problems of a socio-economic nature, problems caused by the deterioration of the environment, and the loss of value orientations of society. The Sustainable Development Goals (SDGs) [1] were formed to prevent these disturbances and define the strategic perspectives of world development that set global growth priorities until 2030.

Despite some progress in the fight against the spread of COVID-19, due, in particular, to effective restrictive measures, mass vaccination of the population (mandatory in some countries of the world), the permanent nature of the course of the disease causes a further increase in the number of victims of the pandemic. As of early 2023, COVID-19 has been recorded in 231 countries and territories with more than 672 million cases, of which about 6.7 million have been fatal [2]. A sudden spike in cases in Shanghai in May 2022 showed [3] that the pandemic can return to peaks even for countries like China, where stringent anti-epidemic measures are in place as part of the "zero-COVID" strategy, which aims to neutralize any facts disease by strict isolation of all infected. The new increase in morbidity and the continuation of this strategy led to mass protests at the end of November 2022, eventually forcing the Chinese government to abandon this policy.

Such a situation leads to a slowdown in the socio-economic development of the world's countries and, accordingly, causes negative consequences for the prospects of achieving the SDGs. Thus, studying the trend of the economic development of the regions during the COVID-19 pandemic is an urgent problem. The study focuses on the global SDG8 and SDG9, which are most related to economic development, in the context of establishing the dynamics of target indicators, the direction of their change during the pandemic period, and compliance with planned trends. The study is hypothetical and limited to data from 2017 to 2021. The war launched by Russia against Ukraine in 2014, and especially its "hot" phase, which began in 2022, caused an additional negative effect on economic development. However, the lack of necessary statistical data does not allow this impact to be considered in the study. Therefore, all calculated estimates are based exclusively on data, the dynamics of which mainly refer to the pandemic period.

2. Literature review

Given the new global disturbances caused by the COVID-19 pandemic, issues of monitoring economic development remain the focus of international institutions and individual scientists. At the same time, separate countries or territories, as well as global development as a whole, are subject to analysis.

Issues of progress in achieving sustainable development goals are not left out. Report [4] provides a brief overview of global and regional development in achieving the SDGs as of the end of 2021. As can be seen from the charts presented, there is a reduction in the pace of development for specific goals. In particular, this situation is observed for SDG8 in terms of ensuring decent work, which is caused by the growth of unemployment rates. On the other hand, the pandemic gave a significant impetus to the development of remote technologies, which spread after 2019 in trade, service provision, banking, and education, reflected in the relevant component of SDG9. It should be noted that part of the actual data from 2019 to 2021 was not available during the preparation of this report, as the pandemic disrupted the established data collection procedures by the relevant government institutions. Therefore, such data were replaced by simulated data, which gives some of the presented results an estimated character.

Annual reports are prepared by Cambridge University specialists, which reflect the state and dynamics of sustainable development indicators. The report prepared based on the values of sustainable development indicators as of the end of 2021 [5] states that the average value of the global SDG index after 2019 has a downward trend. The slow recovery of poor and vulnerable countries explains this result.

The report also presents statistics for individual territories by territory, as well as data for separate countries and territories. The highest value of the SDG index is for EU countries; the lowest is for Sub-Saharan African countries. However, in this study, there is also a lack of relevant values of some from 2015 or 2016, which makes it impossible to assess the impact of COVID-19 on the dynamics of relevant indicators of the SDGs in individual countries and to conduct a complete comparison of the trajectories of achieving the SDGs.

Considerable attention of researchers is paid to the application of tools of statistical analysis and economic-mathematical modeling to build possible trajectories of sustainable development in the context of the impact of COVID-19 According to the results of a study conducted by the Pardee Center for International Futures at the University of Denver in cooperation with UNDP based on data for 2020 several scenarios of global development were constructed in the context of the long-term effect of the pandemic [6]. Considerable attention in the research is also devoted to the analysis of development trends of countries with a low or average value of the human development index. The main conclusion formed by the authors is that one of the strategies enables such countries to get out of the short-term pandemic crisis and return to the trajectory of sustainable development in the long term.

The use of economic and mathematical models based on expert data to assess progress in achieving the SDGs, particularly SDG9, during the COVID-19 pandemic is presented in the article [7]. However, Fulzele et al mainly consider environmental and energy indicators, focusing on something other than sustainable development's economic aspects. Research [8] aims to use machine learning methods to model possible trajectories of sustainable development from up to 2024. Shuai et al concluded that for most of the SDGs, a significant deviation is expected in the progress of achieving the goals compared to the trajectories that could have taken place in the absence of the pandemic and the preservation of development trends. To return to the basic development trajectories, the authors suggest that the main efforts should be devoted to those sectors of the economy that cause the least negative impact on the environment.

Hryhoruk et al [9] considered the construction of a generalized index for assessing the consequences of COVID-19 on the socio-economic development indicators of Ukraine's regions in the context of sustainable development. As a result, it was established that the pandemic had a more significant impact on economic development than the social component. At the same time, the structure of the location of the regions of Ukraine in the space of built integral indicators of economic and social development remained unchanged. Based on a statistical analysis of indicators, the economic consequences of the COVID-19 pandemic for the Polish economy are considered in the article [10]. Dudzik and Brukwicka conclude that Poland's economy suffered less from the consequences of the pandemic than other Eastern European countries. Identifying patterns of the impact of the COVID-19 pandemic on the SDGs, determining the interrelationship of goals in the context of deviations from the planned development trajectories, and the formation of proposals for the development of business recovery strategies based on the theory of catastrophes is presented in the study by Chang et al [11]. Among the shortcomings of the conducted research, it can be noted that the authors do not associate the obtained results with sustainable development goals.

Without reliable statistical data, studies are often based on survey results or expert assessments. In the article [12], based on the analysis of expert data on the impact of COVID-19 on the SDGs, it was concluded that SDG8 is one of the goals for which the effect had particularly negative consequences. Based on a multifactorial criteria analysis, Elavarasan et al determined the priorities of the components of sustainable development. They proposed comprehensive strategies for building optimal trajectories for achieving the SDGs in the post-pandemic period. According to the authors, this will allow returning to pre-pandemic development trajectories faster. In the article [13], based on the results of processing expert data, the impact of the pandemic on the achievement of SDG8 was investigated using the example of Brazil. Report [14] contains a thorough analysis of the achievement of SDG8 in the context of COVID-19, based on the results of a survey of trade unions around the world. At the same time, the emphasis was placed on evaluating indicators related to sub-goals related to obtaining decent work. The vast majority of respondents confirmed the thesis of a significant deviation in the achievement of SDG8 from the planned trajectory for this sub-goal. The authors identified priorities in developing a strategy to achieve SDG8, among which creating new jobs plays a key role. In the study [15], an analysis of economic growth trends in Eastern European countries and an assessment of the effects of the COVID-19 pandemic were carried out. Sheiko and Storozhenko summarized the forecast assessments provided by international institutions and individual experts regarding the development trajectories of Eastern European countries after 2021 and assessed potential risks and threats. However, this study does not link the obtained results to the achievement of the SDGs.

Article [16] contains the results of evaluating changes in the indicators of individual goals, in particular SDG8, due to the negative manifestation of the COVID-19 pandemic. Based on expert data, a ranking of indicators corresponding to the goals selected for analysis was conducted. It was established that one of the most important indicators is the average annual growth rate of GDP per capita, which characterizes economic recovery. According to Marzouk et al, this ranking of indicators will help identify trends in SDG indicators in light of COVID-19 and contribute to creating sustainable development strategies.

The issue of determining priorities in developing a strategy to overcome the consequences of the pandemic to eliminate instabilities and gaps in the interaction between the components of sustainable development is investigated in studies [17–21]. The authors emphasize that under current conditions, developing a long-term sustainable development strategy goes beyond national development policies. This calls for the integration of the SDGs at both the national and international levels, the identification and prevention of potential risks, and the orientation of national development strategies towards inclusive green growth and the development of digital technologies.

The conducted analysis allows us to state the relevance of researching issues of sustainable development and economic recovery of countries in the post-pandemic period. Considering the variability of the development of the current situation, assessing the impact of the pandemic requires constant revision of the forecast estimates and conclusions regarding the development trends of the countries. Highly appreciating the contribution of scientists and international institutions to the study of the impact of COVID-19 on the achievement of the SDGs and the development of approaches to strategies for the recovery of development, including national economies, in the post-pandemic period, it should be noted that the studies are mainly based on expert data, which contributes a subjectivity in the obtained results. It should also be noted that at the level of European countries, such studies mainly concern EU member states. The purpose of our research is to identify the impact of the COVID-19 pandemic on the economic development of countries to achieve sustainable development goals and evaluate progress trends in the post-pandemic recovery of the economies of Eastern Europe countries by analyzing quantitative data from official statistics. The object of the study is the economic development of Eastern European countries in the conditions of the COVID-19 pandemic. The subject of the study is models and methods of assessing the impact of the COVID-19 pandemic on the country's economic development.

Following the specified goal, the formulated object, and the subject of the research, the research objectives are the analysis of economic development indicators of Eastern European countries in the context of SDG8 and SDG9 in the period from 2017 to 2021, and the identification of the main trends of their change; comprehensive assessment of progress in the recovery of Eastern European countries economic development in the context of SDG8 and SDG9 in the period after 2021.

3. Research methodology

Sustainable development goals are interrelated, so the assessment of progress in achieving them must be comprehensive. This requires the processing of significant amounts of data; therefore, in our study, we will limit ourselves to the analysis of those indicators that are directly related to economic development in the context of the indicators of the goals of SDG8 and SDG9. For the research, we used the toolkit for analyzing the dynamics of indicators – to identify existing trends in their change; forecasting methods – for assessing the trends of changes in indicators for the following periods; integrated assessment technologies – to obtain a comprehensive assessment of the progress of economic development in the post-pandemic period; generalization – for interpreting the obtained results and formulating conclusions in the context of research objectives.

The information base of the research is publications on the research topic, data from a Metadata repository for SDG Indicators [22], a databank of the World Bank [23], the statistical portal of ILO [24], and results of the author's studies.

According to [25], statistical data for SDG8 after 2015 are available for only 60 percent of countries' indicators. For SDG9, this share of data is 70 percent. This makes it difficult to carry out a comprehensive analysis of progress in economic development, in particular, and in the context of the indicators defined in [1] for the goals of SDG8 and SDG9. Therefore, those indicators supported by the necessary statistics were selected for the study.

As objects for evaluating economic development trends, we will choose the countries of Eastern Europe: Bulgaria, Czechia, Hungary, Moldova, Poland, Romania, Slovak Republic, and Ukraine. Most of the countries are members of the EU. According to the World Bank, as of 2021, Ukraine had the status of a country with a Lower middle-income economy; Bulgaria and Moldova had level of Middle-income economies; the rest of the countries belong to the category of countries with High-income industrial economies [26]

We select the period from 2017 to 2021 for the research. The choice of such a period is due to several reasons:

(i) the period from 2017 to 2019 refers to the pre-pandemic period and was used to determine the direction of the impact of COVID-19 on the economic development of countries in 2020;

(ii) the following period is limited to 2021 since, for the vast majority of indicators, there is no data for 2022, which is provided in the section of country statistics by world institutions, in particular, the World Bank, the International Labor Organization, the United Nations Statistics Division.

The active phase of Russian aggression against Ukraine, which began in February 2020, caused new global challenges to the progress of economic development in Ukraine and other Eastern European countries. Hence, their consideration requires a separate study.

We use visual analysis of their values to identify trends in changing indicators. Assessing the predictive values of indicators we execute using the Holt-Winters method [27]. It belongs to the group of adaptive forecasting methods and can be successfully used for a series of dynamics in the absence of a clear trend in changing indicators.

To assess progress in the recovery of the economic development of the countries of Eastern Europe in the context of SDG8 and SDG9 in the period after 2021, we will use the comprehensive index method, which will allow us to comprehensively take into account the change in the values of all partial indicators and reduce them to one measure [9]. This simplifies the interpretation of the obtained result.

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4. Results and discussions

Let's consider the dynamics of indicators that determine the economic development of the countries selected for the study. We have chosen the following indicators: GDP annual growth (percent); Growth Rate of Per Capita GDP at constant 2015 prices in US Dollars (percent); Industry (including construction), value added (annual growth, percent); Exports of goods and services (annual growth, percent); Imports of goods and services (annual growth, percent); Unemployment rate, total (percent); Employment to population ratio, 15+, total (percent).

The first two indicators are among the determining factors in analyzing the country's economic development, as they accumulate all economic activity results. The third indicator characterizes the industry's contribution to economic development and is related to SDG9. The fourth and fifth indicators reflect the foreign economic ties of economic development. The last two are employment indicators, primarily associated with providing decent work as one of the sub-goals of SDG8. For ease of analysis, we will also include the estimated values of indicators for 2022 in the tables together with the initial data. This will simplify our analysis of the expected trend and simplify the calculations of the integral indicator.

The values of GDP change indicators are shown in table 1 and table 2.

The analysis of the presented values shows that in 2020 there was a significant drop in the GDP value, which was reflected in the negative values of the corresponding growth rates. In 2021, GDP growth resumed, but it should be taken into account that such a result was obtained in comparison with the previous year and does not reflect the real change in GDP. The highest growth was observed for Moldova and the Slovak Republic. In general, GDP growth was higher for countries with high-income industrial economies, except Moldova, which belongs to the

Table 1. GDP annual growth (percent).

Country	2017	2018	2019	2020	2021	2022
Bulgaria	2.8	2.7	4.0	-4.0	7.6	5.7
Czechia	5.2	3.2	3.0	-5.5	3.5	2.1
Hungary	4.3	5.4	4.9	-4.5	7.1	5.3
Moldova	4.7	4.3	3.7	-7.4	13.9	10.3
Poland	5.1	5.9	4.4	-2.0	6.8	5.4
Romania	8.2	6.0	3.9	-3.7	5.1	3.7
Slovak Republic	2.9	4.0	2.5	-3.4	3.0	2.0
Ukraine	2.4	3.5	3.2	-3.8	3.4	2.3

Table 2. Growth Rate of Per Capita GDP at constant 2015 prices in US Dollars (percent).

Country	2017	2018	2019	2020	2021	2022
Bulgaria	3.5	3.4	4.8	-3.4	8.5	6.6
Czechia	4.9	2.9	2.6	-5.7	5.4	3.6
Hungary	4.5	5.5	4.9	-4.3	7.6	5.7
Moldova	6.5	6.2	5.4	-6.4	14.8	11.3
Poland	5.1	5.9	4.5	-1.8	7.3	5.8
Romania	8.8	6.7	4.4	-3.1	5.9	4.5
Slovak Republic	2.8	3.9	2.4	-3.5	3.2	2.2
Ukraine	2.8	4.0	3.8	-3.1	4.3	3.2

group of countries with middle-income economies. According to the estimates of the values of the indicators for 2022, we note a decrease in the GDP growth rate, which is explained by the higher values of the indicators in 2021 compared to 2020.

The change in the values of the "indicator Industry (including construction), value added" is shown in table 3. Let's draw attention to the fact that for most countries, except Hungary, there was a downward trend in the values of the indicator from 2017 to 2020. in Hungary, such a decrease occurred only in 2020. As in the case of GDP, 2020 turned out to be the most critical year. The reduction or suspension of business activity of many production structures explains this. The year 2021 was characterized by the recovery of businesses in most countries, although the negative trend of the change in the indicator remained for Moldova. Estimated values of the indicator for 2022 also show a tendency to decrease values.

Let's consider the indicators reflecting the volume of foreign trade. This field of activity was also significantly limited due to quarantine restrictions. However, such restrictions gave significant impetus to the development of online trade. Values of indicators are shown in table 4 and table 5.

The analysis of the tables shows that the given indicators in the pre-pandemic period had a changing trend, but in 2020 they also significantly decreased. The most significant export decrease occurred in Bulgaria, the Czech Republic, Moldova, and Romania. For the import indicator, the most significant decrease occurred in the Czech Republic and the Slovak Republic. In 2021, there was a significant increase in the volume of export-import transactions, and the growth rates were the highest during the studied period for all countries except the Czech Republic and Ukraine. For Ukraine, in 2021, the negative trend of decreasing the value of the

Table 3. Industry (including construction), value added (annual growth, percent).

Country	2017	2018	2019	2020	2021	2022
Bulgaria	1.0	0.0	-0.1	-8.2	1.7	0.0
Czechia	6.6	1.4	1.9	-9.9	3.3	1.1
Hungary	4.4	4.3	4.5	-7.9	6.6	4.3
Moldova	3.8	8.3	6.0	-2.8	-0.7	-0.7
Poland	1.2	5.8	3.4	-4.5	3.4	2.2
Romania	6.4	4.5	-0.4	-4.2	4.1	2.6
Slovak Republic	1.5	7.0	3.9	-12.6	2.5	0.1
Ukraine	1.8	2.7	2.3	-3.2	2.6	1.7

Table 4. Exports of goods and services (annual growth, percent).

Country	2017	2018	2019	2020	2021	2022
Bulgaria	5.8	1.7	4.0	-10.4	11.0	7.4
Czechia	7.2	3.7	1.5	-8.0	6.9	4.4
Hungary	6.5	5.0	5.4	-6.1	10.3	7.6
Moldova	10.9	7.2	8.2	-9.6	17.5	13.1
Poland	9.0	6.8	5.3	-1.1	12.5	10.2
Romania	7.8	5.3	5.4	-9.5	12.5	8.9
Slovak Republic	3.7	5.1	0.8	-6.4	10.6	7.7
Ukraine	3.9	-1.4	7.3	-5.8	-10.4	-9.2

Table 5. Imports of goods and services (annual growth, percent).

Country	2017	2018	2019	2020	2021	2022
Bulgaria	7.4	5.8	5.2	-4.3	10.9	8.4
Czechia	6.3	5.8	1.5	-8.2	13.3	9.6
Hungary	8.4	7.0	8.2	-3.9	9.1	7.1
Moldova	11.0	9.7	6.2	-5.0	19.2	15.1
Poland	9.9	7.5	3.2	-2.4	16.1	12.9
Romania	11.5	8.6	8.6	-5.2	14.6	11.4
Slovak Republic	4.1	4.8	2.2	-8.2	12.1	8.6
Ukraine	12.9	2.8	5.7	-6.4	12.7	9.5

Table 6. Unemployment rate, total (percent).

Country	2017	2018	2019	2020	2021	2022
Bulgaria	6.2	5.2	4.2	5.1	5.4	5.5
Czechia	2.9	2.2	2.0	2.5	2.9	2.9
Hungary	4.2	3.7	3.4	4.3	4.1	4.2
Moldova	4.1	4.1	5.1	3.8	4.0	4.1
Poland	4.9	3.8	3.3	3.2	3.4	3.4
Romania	4.9	4.2	3.9	5.0	5.2	5.2
Slovak Republic	8.1	6.5	5.8	6.7	6.7	6.8
Ukraine	9.5	8.8	8.2	9.1	8.9	9.1

export indicator continued, and the rate of decrease was the highest. The year 2022 showed a reduction in the growth rate of indicators, and for Ukraine, the negative trend for the import indicator continued, albeit on a smaller scale.

Analyzing the indicators of unemployment and employment (table 6 and table 7), the following conclusions can be drawn. Regarding unemployment, from 2017 to 2019, there was a gradual decrease in the indicator's value. In 2020, the unemployment rate increased in all countries except Poland and Moldova. In 2021, the trend of unemployment growth continued for all countries except Ukraine. However, the given indicators may not reflect the actual state of the labor market, as they are obtained based on estimates calculated by the ILO [24]. The calculated estimated values of the unemployment rate for 2022 showed that the unemployment rate might remain practically at the previous level. However, the recovery of business activity may be the reason for the decrease in the rate value.

Regarding the employment indicator, from 2017 to 2019, there was also a trend of increasing values for all Eastern European countries. In 2020, the indicator's value decreased for all countries except Romania, and this trend continued in 2021 for all countries except Hungary, Poland, Slovak Republic, and Ukraine. Estimated values for 2022 show an increase in the level of employment, which is consistent with the thesis of the recovery of business activity.

In general, evaluating the trends of indicators, we can conclude that the pandemic really had a negative impact on the economic development of countries, which was reflected in the reduction of their growth rates. The most negative phenomena appeared for the indicators of Moldova, Romania, and Ukraine, and the least – for Poland.

Let's conduct a comprehensive assessment of the level of economic development. For this purpose, we will construct a composite indicator named the comprehensive index of economic

Table 7. Employment to population ratio, 15+, total (percent).

Country	2017	2018	2019	2020	2021	2022
Bulgaria	51.9	52.4	54.2	52.7	52.6	53.8
Czechia	58.5	59.2	59.2	58.3	58.0	59.3
Hungary	53.9	54.6	55.1	54.5	56.7	57.5
Moldova	40.5	35.8	40.1	38.8	37.1	38.3
Poland	53.7	54.2	54.4	54.3	55.1	56.1
Romania	52.2	52.7	53.0	52.3	49.5	51.2
Slovak Republic	55.1	55.9	56.3	55.1	56.3	57.3
Ukraine	51.0	51.4	51.7	50.1	50.2	51.3

Table 8. Comprehensive index of economic development.

Country	2017	2018	2019	2020	2021	2022
Bulgaria	0.51	0.48	0.53	0.23	0.64	0.58
Czechia	0.64	0.57	0.53	0.23	0.64	0.58
Hungary	0.59	0.59	0.60	0.26	0.68	0.62
Moldova	0.55	0.53	0.51	0.14	0.70	0.61
Poland	0.59	0.62	0.56	0.35	0.70	0.65
Romania	0.66	0.60	0.54	0.25	0.63	0.58
Slovak Republic	0.49	0.57	0.50	0.20	0.59	0.54
Ukraine	0.50	0.45	0.51	0.23	0.45	0.42

development. For the comparability of the results, the values for all countries for each partial indicator will be combined into one sample. We will use the rules given in [9] to normalize partial indicators. At the same time, we take into account that the unemployment rate is a disincentive. Convolution of partial indicators was carried out according to the rule of linear additive convolution. Since we do not have any a priori information about the importance of certain partial indicators, we will choose the same weighting coefficients for their convolution. The results are presented in table 8.

The analysis of the values of the comprehensive indicator allows us to state that in 2022, its lowest values for the entire studied period took place. The most significant drop occurred in Moldova, while the economy of Poland was the most stable. In 2021, an increase in the values of the comprehensive indicator was observed, and the highest values were for Moldova and Poland. The phenomenon of Moldova is explained by the significant growth of individual indicators, which in turn is determined by their low absolute values compared to other Eastern European countries. The assessment of the value of the generalized indicator of economic development for 2022 shows a slight decrease in values, which is consistent with the conclusions made during the analysis of the partial indicators that are components of this generalized indicator.

More accurate estimates of the economic development of the countries of Eastern Europe in 2022 could be obtained, taking into account either the actual values of the indicators, which are currently unavailable, or their expert assessments. Currently, such estimates are available only for GDP indicators.

5. Conclusions

Identifying economic development trends both for the country's economic system as a whole and at the level of its separate regions remains an important task. Such research acquires special significance in periods of global challenges, one of which was the COVID-19 pandemic. Deviation from the trajectory of achieving the stated goals was observed even in the pre-pandemic period, but the COVID-19 pandemic exacerbated the existing problems. It isn't easy to assess all the consequences since this process has not yet ended. In addition, the active phase of Russian aggression created new challenges for sustainable development. However, identifying trends in the change of target indicators in terms of individual SDGs, in particular SDG8 and SDG9, is an urgent task.

The study of the indicators' values from 2017 to 2019 showed that gradual progress in economic development was generally observed despite the lack of clear trends for individual indicators. This allows us to conclude on the gradual improvement and the achievement of the target indicators for SDG8 and SDG9.

The analysis showed that 2020 was the most critical year by all indicators, which led to a significant deviation from the planned trajectory of sustainable development. This finding is consistent with research results provided by other scientists and research institutions. In 2021, the situation began to improve, reflected in the indicator values' growth. Deviations occurred only in individual values for Ukraine and the Slovak Republic. Ukraine had a lower level of development according to the selected indicators, while Poland demonstrated the highest stability of its economy. At the same time, despite the limitations of statistical data, the obtained results showed that for many indicators, the rates of their decline in 2020 for Ukraine were lower than for other Eastern European EU member countries. Estimated values for 2022 showed a decrease in the growing trend of the indicators selected for analysis. This can be explained by the fact that the vast majority of indicators are relative and depend on the previous levels of the corresponding absolute indicators. To comprehensively take into account all indicators, we have built a generalized indicator of economic development. The analysis of its values confirmed the earlier conclusions regarding economic development trends in 2020 and 2022.

Study results can be considered when planning economic development strategies as auxiliary analytical information.

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References

[1] United Nations Department of Economic and Social Affairs 2023 SDG Indicators. Global indicator framework for the Sustainable Development Goals and targets of the 2030. Agenda for Sustainable Development URL https://unstats.un.org/sdgs/indicators/indicators-list/
[2] Worldometers 2023 COVID-19 Coronavirus Pandemics URL https://www.worldometers.info/coronavirus/#countries
[3] Associated Press 2022 Shanghai Moves Toward Ending 2-Month COVID-19 Lockdown 2022 URL https://cutt.ly/oKpzfpL

[4] United Nations 2022 Sustainable Development Goals Progress Chart 2022 URL https://unstats.un.org/sdgs/report/2022/progress-chart-2022.pdf

[5] Sachs J D, Lafortune G, Kroll C, Fuller G and Woelm F 2022 *Sustainable Development Report 2022. From Crisis to Sustainable Development: the SDGs as Roadmap to 2030 and Beyond* (Cambridge University Press) URL https://doi.org/10.1017/9781009210058

[6] Abidoy B, Felix J, Kapto S and Patterson L 2021 Leaving No One Behind: Impact of COVID-19 on the Sustainable Development Goals (SDGs) Flagship publication 2 United Nations Development Programme and Frederick S. Pardee Center for International Future New York, NY and Denver, CO URL https://cutt.ly/FJLhbC9

[7] Fulzele R, Fulzele V and Dharwal M 2022 *Materials Today: Proceedings* **60** 873–879 ISSN 2214-7853 4th Online International Conference on Science & Engineering of Material URL https://doi.org/10.1016/j.matpr.2021.09.517

[8] Shuai C, Zhao B, Chen X, Liu J, Zheng C, Qu S, Zou J P and Xu M 2022 *Fundamental Research* URL https://doi.org/10.1016/j.fmre.2022.06.016

[9] Hryhoruk P, Khrushch N, Grygoruk S, Gorbatiuk K and Prystupa L 2021 *European Journal of Sustainable Development* **10**(1) 63–80 URL https://doi.org/10.14207/ejsd.2021.v10n1p63

[10] Dudzik I and Brukwicka I 2021 *VUZF Review* **6** 15–21 URL https://www.researchgate.net/publication/357374954

[11] Chang S E, Brown C, Handmer J, Helgeson J, Kajitani Y, Keating A, Noy I, Watson M, Derakhshan S, Kim J and Roa-Henriquez A 2022 *International Journal of Disaster Risk Reduction* **80** 103191 ISSN 2212-4209 URL https://doi.org/10.1016/j.ijdrr.2022.103191

[12] Elavarasan R M, Pugazhendhi R, Shafiullah G M, Kumar N M, Arif M T, Jamal T, Chopra S S and Dyduch J 2022 *Environmental Science and Pollution Research* **29**(23) 33957–33987 ISSN 1614-7499 URL https://doi.org/10.1007/s11356-021-17793-9

[13] Anholon R, Rampasso I S, Martins V W B, Serafim M P, Leal Filho W and Quelhas O L G 2021 *Kybernetes* **50**(5) 1679–1686 URL https://doi.org/10.1108/K-12-2020-0833

[14] International Labour Organization 2021 *The likely impact of COVID-19 on the achievement of SDG 8: A trade union opinion survey ILO-ACTRAV* (Turin, Italy) URL https://cutt.ly/gJXvNpD

[15] Sheiko I and Storozhenko O 2021 *Economy and Society* **25** URL https://doi.org/10.32782/2524-0072/2021-25-83

[16] Marzouk M, Elshaboury N, Azab S, Megahed A and Metawie M 2022 *International Journal of Disaster Risk Reduction* **82** 103319 ISSN 2212-4209 URL https://doi.org/10.1016/j.ijdrr.2022.103319

[17] Shulla K, Voigt B F, Cibian S, Scandone G, Martinez E, Nelkovski F and Salehi P 2021 *Discover Sustainability* **2**(1) 15 ISSN 2662-9984 URL https://doi.org/10.1007/s43621-021-00026-x

[18] Shulla K 2021 The COVID-19 pandemic and the achievement of the SDGs *Virtual Inter-agency Expert Group Meeting on Implementation of the Third United Nations Decade for the Eradication of Poverty (2018-2027) "Accelerating Global Actions for a World without Poverty" 24-27 May 2021* URL https://cutt.ly/TJXZrVU

[19] Barbier E B and Burgess J C 2020 *World Development* **135** 105082 ISSN 0305-750X URL https://doi.org/10.1016/j.worlddev.2020.105082

[20] Hörisch J 2021 *Sustainability Accounting, Management and Policy Journal* **12**(5) 180–198 URL https://doi.org/10.1108/SAMPJ-08-2020-0277

[21] Hryhoruk P M, Khrushch N A and Grygoruk S S 2021 Modeling structural changes in the regional economic development of ukraine during the COVID-19 pandemic *Proceedings of the Selected and Revised Papers of 9th International Conference on Monitoring, Modeling & Management of Emergent Economy (M3E2-MLPEED 2021), Odessa, Ukraine, May 26-28, 2021* (*CEUR Workshop Proceedings* vol 3048) ed Kiv A E, Soloviev V N and Semerikov S O (CEUR-WS.org) pp 180–198 URL https://ceur-ws.org/Vol-3048/paper12.pdf

[22] United Nations 2022 SDG Indicators. Metadata repository URL https://unstats.un.org/sdgs/metadata

[23] The World Bank 2023 DataBank. World Development Indicators URL https://databank.worldbank.org/source/world-development-indicators#

[24] ILOSTAT 2023 Data tools to find and download labour statistics URL https://ilostat.ilo.org/data/#

[25] United Nations 2022 The Sustainable Development Goals Report 2022 URL https://unstats.un.org/sdgs/report/2022/The-Sustainable-Development-Goals-Report-2022.pdf

[26] World Bank 2022 World Bank list of economies 2021-22 URL https://cutt.ly/Y5auSmS

[27] SolarWinds 2019 Holt-Winters Forecasting and Exponential Smoothing Simplified URL https://orangematter.solarwinds.com/2019/12/15/holt-winters-forecasting-simplified/

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Black Sea region in world grain trade and problematic aspects of development

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Abstract. The research objective is an analysis of the participation of the Black Sea Basin countries (Ukraine, Russia, Kazakhstan, Bulgaria and Romania) in world grain trade. We started this research before the start of Russia's military actions in Ukraine, and completed it during these actions, so we have a vision of the situation before and after start of war. Subject of research: stability of grain supplies (wheat, corn, barley) from the Black Sea region as a whole and from some of its countries. Results of the research: The research revealed the growing role of the Black Sea region in the pre-war period in the world grain market and identified its key leaders. The share of the Black Sea region in world trade in wheat increased to 34%, barley – to 40,6%, corn – to 25,3% in 2019/2020 marketing year. The calculated coefficients of variation confirmed the decrease in the scattering of grain exports in 2015-2020 vs. 2010-2015, which indicates an increase in stability and reliability of supply in this period. The situation changed radically after the Russian invasion of Ukrainian territories. The maritime logistics corridors of Ukraine that is the one of the key players in this region, were blocked and started working only five months later, but not at full capacity. All these events had its destructive consequences for world trade, in particular, the increase in world prices, disruption of the stability of grain supplies from the Black Sea region and the destruction of established logistics corridors, etc.

1. Introduction

The global problem of the modern world is the prospect of lack of food resources for the ever-growing population of the globe. International organizations (FAO, IFAD, UNICEF, etc.) warn that before the COVID-19 pandemic, 690 million people didn't receive enough food, i.e., 8,9% of the world's population, and the continuation of this trend could lead to an increase in malnutrition up to 840 million tons in 2030 [1]. Thus, the problem of food shortages will only deepen in the near future.

A logical question arises, which countries will be able to provide the growing needs of the world in food? Therefore, the research is devoted to the study of the role of the Black Sea region in world grain trade.

This article is structured as follows. The first section focuses on the relevance of this topic. The second and third sections present a review of the literature and methodological approaches to solving the tasks. The fourth section demonstrates the results of researches, namely analyzes the place and role of the Black Sea region in world grain trade (wheat, corn, barley), assesses the stability of grain supplies from this region as a whole and its individual countries, individual aspects of the impact of the war on world prices were analyzed, a SWOT analysis of Ukraine's competitive positions on the world grain market was carried out. The fifth section summarizes this research and identifies areas for further research.

2. Literature review

With the strengthening of the role of the Black Sea region in world trade in the last 10 years, it was published scientific papers which illuminate the behavior and pricing policy of exporting countries in this region. However, the export policy of individual countries (Ukraine, Russia, etc.) is illuminated more often and its cumulative influence on world trade is analyzed less often.

In particular, Götz et al [2] analyze the negative influence of export restrictions in 2007-2008 on the domestic grain market of exporting countries of Ukraine and Russia and its integration into the world market. However, many changes have taken place since then, with some countries abandoning 'manual' methods of regulation and others abandoning them altogether. In the long term, the regulation of grain exports should be reduced mainly to a system of economic measures, but at the moment, government participation is necessary as a driver in the development of production and logistics infrastructure [3].

One of the conclusions of Svanidze and Götz [4] is the following: unforeseen policy interventions for grain markets further increase the level of grain market uncertainty and, hence, costs of grain trade in Russia. At the same time, the authors consider the increase of spatial market efficiency of grain markets in Russia as the driver of increasing the country's export potential. Together, the conducted study of the state of Russian transport capabilities has revealed the lack of development of the latter, especially railway transport and grain transshipment capabilities in seaports, which prevents an increase in the volume of grain exports to strategic foreign partners [5].

Ukraine doesn't apply strict restrictions and prohibitions, there is a fairly democratic Memorandum of Understanding between the relevant ministry and economic entities – grain exporters and there has never been a 'manual' restriction of exports. One of the main problems in the export of Ukrainian grain is a high share of logistics costs, which reaches 35% of the final cost of production [6].

Some scientists believe that over the last two decades, the Black Sea region developed to be a key global exporting region for corn and wheat [7]. We fully agree with Heigermoser et al, who note that many market participants grapple with insufficient knowledge of factors that drive Black Sea spot prices, while effective futures markets that could facilitate price discovery and risk management are still missing. That's why these factors need more profound study.

Among recent studies, the scientific work of Gafarova et al [8], which examines the price behavior of the main exporters of wheat from the Black Sea region (Ukraine, Russia and Kazakhstan), identifies importing countries in which price discrimination is applied and countries where perfect competition does not allow it. In Goychuk et al [9] were performed tests of market price co-integration (Johansen maximum likelihood test and residual-based tests) as well as threshold error correction techniques were performed for this purpose. The results suggest that Russian wheat prices were co-integrated with EU and U.S. Ukrainian wheat prices were found to be co-integrated with French wheat prices only.

The countries of the Black Sea region have not escaped illicit financial Flows in export operations with agricultural products. The unstable state of the economy of these countries has led to significant financial losses in grain exports [10]. The authors' main contributions are discovered asymmetry of mirror data such as price, trade value and weight of Ukrainian grain.

China has become an increasingly important actor in the Black Sea Region (BSR), and this looks set to continue in the future [11]. According to the author, potential Ukrainian economic growth suggests that Kyiv has the potential to be a key driver in increasing maritime trade and future investment by China in the BSR. In fact, this is exactly what happened before the war

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in Ukraine. After February 24, 2022, significant transformations took place with the stability of the supply of grain and other agro-food products from this region.

There is a great deal of uncertainty about the impact of the war on food security is recognized by most experts and scientists, including Berkhout et al [12], Glauben et al [13], as it is not even possible to foresee the end date of the war.

However, it is clear that food security in certain regions of the world today is a significant threat [14, 15]. The war in Ukraine is likely to have the greatest impact on regions that depend on imported wheat, particularly from Russia and Ukraine, as a key part of their diets. Even countries that are less dependent on wheat imports from the Black Sea region could face food security issues, as designated by Glauben et al [13].

FAO warns: ‘In the short term, the alternatives to falling exports from Ukraine and Russia seem limited. For example, according to the FAO, wheat and maize harvests in Canada and the US have been disappointing, Argentina is applying export restrictions to combat domestic inflation, and Australia can no longer deliver owing to logistical bottlenecks’ [14].

3. Data and methodology

Time series, arithmetic averages, the method of expert assessments, extrapolations, etc. were used to assess the influence of the Black Sea basin countries on world trade.

The methodological approach involved the calculation of scattering indicators in sales of goods for the selected interval relative to the arithmetic mean sales of this good for the selected period of time to analyze the stability of export deliveries.

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \tilde{x})^2}{n}}$$

σ – the standard deviation
x_i – the number of sales of good per interval
n – number of intervals
$\tilde{x}$ – arithmetic mean

The arithmetic mean is determined by the formula:

$$\tilde{x} = \frac{1}{n}\sum_{i=1}^{n} x_i = \frac{1}{n}(x_1 + \ldots + x_n)$$

We needed the standard deviation to calculate the coefficients of variation, which more accurately characterize the scattering and reflect the stability of export supplies in the selected time interval.

$$V = \frac{\sigma}{\tilde{x}}$$

V – the coefficients of variation
σ – the standard deviation
$\tilde{x}$ – arithmetic mean

For data extrapolation, the exponential smoothing method was used, which is the most effective when developing medium-term forecasts.

$$U_{t+1} = \alpha \times y_t + (1 - \alpha) \times U_t$$

U_{t+1} – predicted indicator
t – period preceding the forecast
$t + 1$ – forecast period
α – smoothing parameter

y_t – actual indicators for the period preceding the forecast period
U_t – exponentially weighted average for the preceding period predictive

The Delphi method is used to develop the SWOT matrix. The Delphi method relies on experts who are knowledgeable about a certain topic so they can forecast the outcome of future scenarios, predict the likelihood of an event, or reach consensus about a particular topic. For our research, expert opinion was obtained from farmers who are members of the PU 'Agrarian Union of Ukraine'.

The information database of our researches was the data of UN Comtrade [16], The Foreign Agricultural Service (FAS) of United States Department of Agriculture [17], and AgriSupp of the consulting agency UkrAgroConsult [18].

4. Research findings and discussion

4.1. Black Sea region in world grain trade: before war

Research has shown that the key players in world grain trade from the Black Sea region were such countries: Ukraine, Russia, Kazakhstan, Romania and Bulgaria. All these countries (except Kazakhstan) have access to international waterways, its own ports and port elevators, the number of which has been increasing in recent years. Kazakhstan is located within the continent and away from sea routes, so the logistics of this country to the Black Sea and Azov ports runs through the territory of Russia [19].

Over the ten years (2010–2020), grain sales by the above-mentioned countries have increased significantly: wheat – 3,7 times, corn – 6 times, barley – 1,7 times (figure 1).

A growing trend is still evident despite of fluctuations in export volumes. Manufacturers and

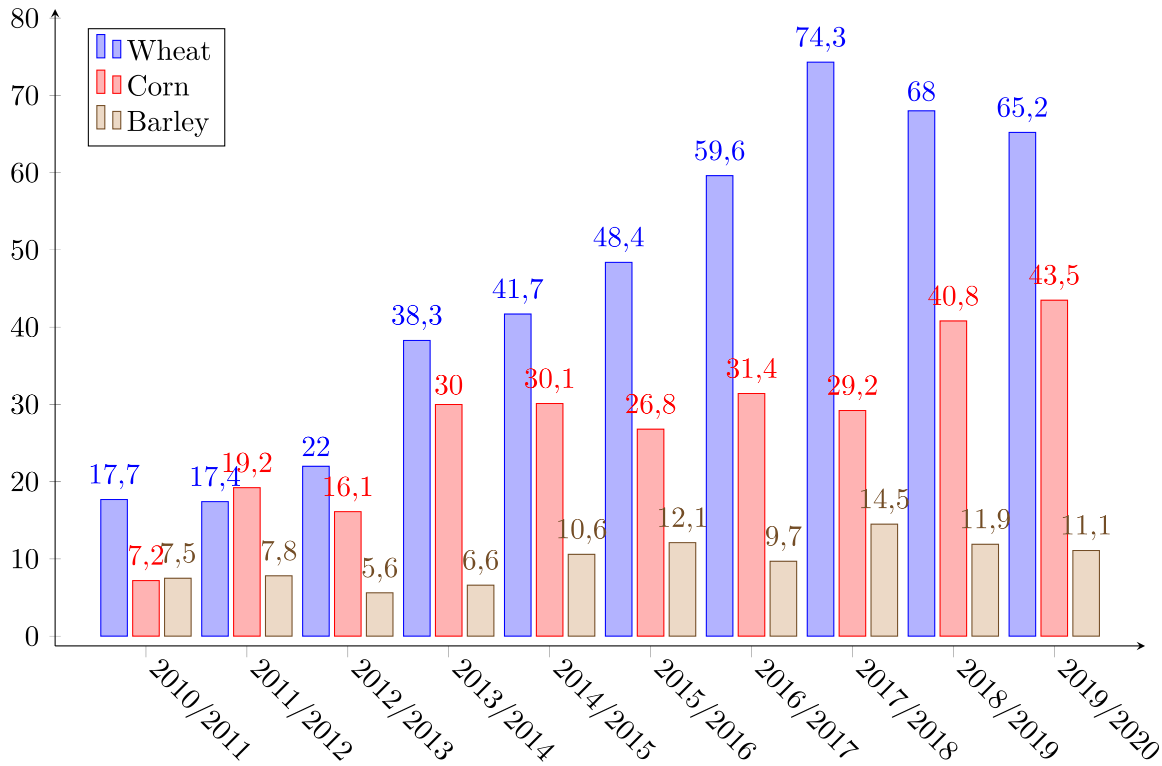

Figure 1. Dynamics of wheat, corn and barley exports by the Black Sea basin countries in the 2010/2011 – 2019/2020 marketing years, million tons.

exporters received more income from the sale of products for export. Governments have also realized the undeniable benefits of receiving dollar-denominated export earnings, so it is now prudent to impose any export restrictions and the situation described by Götz et al [2] is no longer repeated.

Calculations based on AgriSupp [18] and FAS [17] data show that the share of the Black Sea region in world wheat trade increased from 13,2% in the 2010/2011 marketing year (hereinafter – MY) to 34% in 2019/2020 MY, corn – from 7,9% to 25,3%. The share of the Black Sea region in world barley exports, on the contrary, decreased from 47% in 2010/2011 MY to 40% in 2019/2020 MY.

The countries of the Black Sea basin competed with each other, so there are leaders in the export of certain crops. Russia was the leader in wheat exports with a share of 52,1% of the total sales of wheat from the Black Sea region in 2015/2020 – 2019/2020 MY (figure 2).

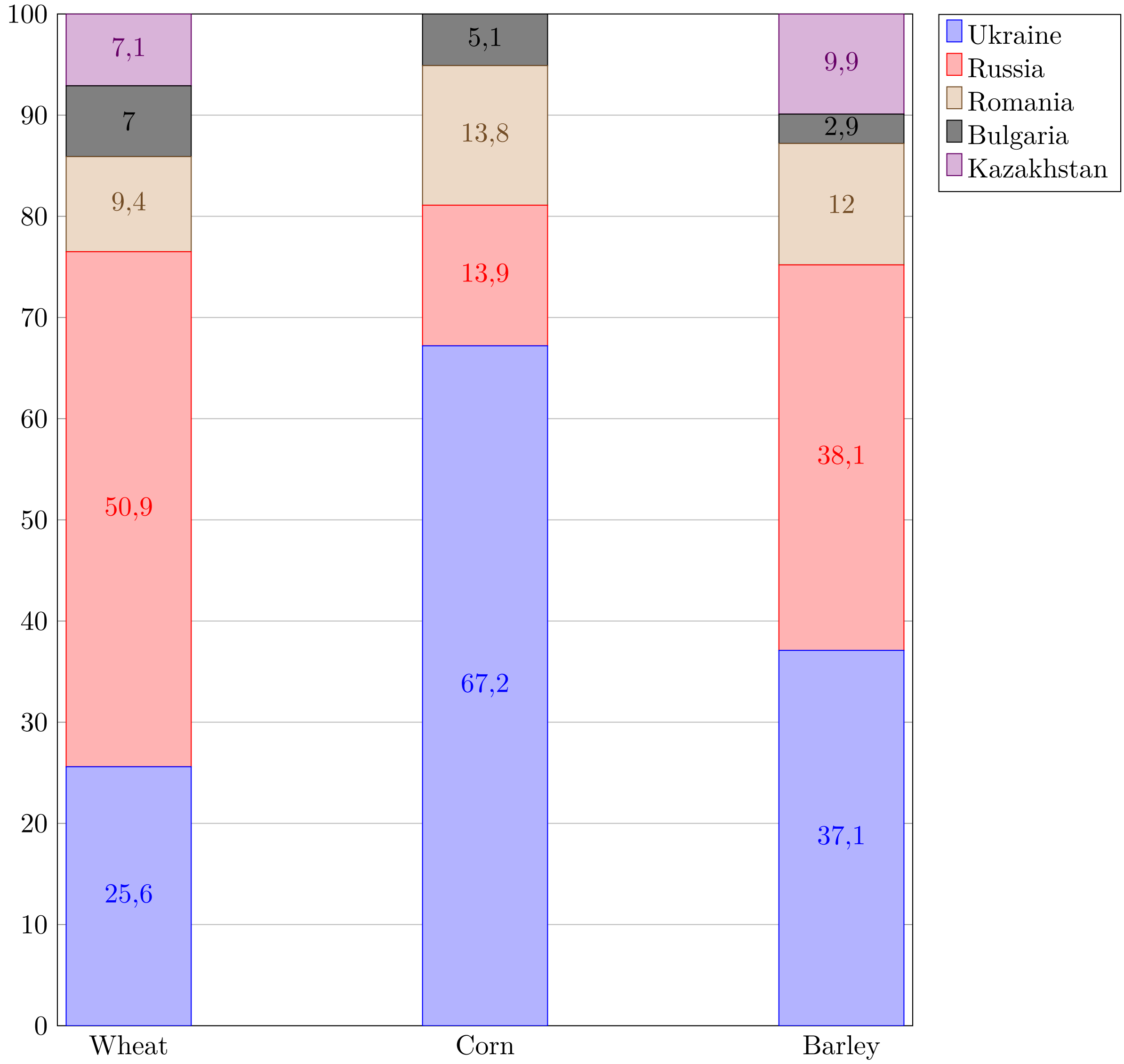

Figure 2. The share of individual countries in the Black Sea region in exports of wheat, corn and barley, on average over the past 5 years (2015/2016 – 2019/2020 MY), %.

Ukraine was the undisputed leader in corn exports, with a share of 67,2%. The share of barley sales in Ukraine and Russia is approximately at the same level – 37% and 38% of the total export of barley from the Black Sea region, respectively.

The issue of stability of supplies from this region is relevant with the strengthening of the role of grain-exporting countries from the Black Sea basin. Naturally, deviations in the time series were quite significant in the period of 10 years (2011–2020) (table 1), because during this period there was a significant increase in supplies of wheat and corn from the Black Sea region to the world market, as well as fluctuations in barley supplies. However, it is important to understand whether the fluctuations of export indicators in recent years are equalizing. Is the Black Sea region able to ensure the achieved high rates of exports? How reliable is the region as a key supplier of grain resources to the world market?

Table 1. Coefficients of variation of grain exports from the Black Sea region and individual leading countries, 2011-2020, %.

Country	Wheat			Corn			Barley		
	V (2011-2020)	*V* (2011-2015)	*V* (2016-2020)	*V* (2011-2020)	*V* (2011-2015)	*V* (2016-2020)	*V* (2011-2020)	*V* (2011-2015)	*V* (2016-2020)
The Black Sea basin countries									
Ukraine	43,5	29,5	16,0	37,5	37,8	24,5	33,9	47,4	12,3
Russia	57,6	68,8	16,5	53,0	62,1	24,8	42,9	58,8	18,9
Kazakhstan	37,6	50,1	16,9	...	...	...	61,2	53,0	31,9
Bulgaria	15,9	26,1	12,2	31,8	19,2	38,1	32,3	50,0	30,0
Romania	35,3	38,7	11,7	45,1	51,7	33,1	34,4	38,5	23,3
Total	44,8	38,1	13,9	37,8	42,5	19,2	27,4	22,0	13,2
Countries are the leaders in the export of grain in the world									
USA	15,0	14,9	10,3	24,4	29,0	11,1			
EU	25,1	27,9	20,8				28,2	36,8	13,0
Canada	12,5	15,1	6,7				28,2	14,1	26,2
Brazil				35,2	30,1	23,1			
Argentina				34,5	19,6	24,7			
Australia	28,9	14,2	35,7				27,3	15,2	29,7

It should be noted that, the Black Sea countries tried to maintain the image of reliable suppliers of grain on the world market in 2011-2020, learning some lessons of failed ‘manual’ management, which traditionally ended with losses for business and the state budget.

We calculated the coefficients of variation with a breakdown of the time series at intervals of 5 years. Russia showed the largest fluctuations in the export of wheat, corn and barley – 62-69% in the first five-year period (2011-2015), (table 1, figure 3). Grain supplies from other countries of the Black Sea basin are also not stable: the variability of indicators from year to year is significant, on average 30-50%.

The scattering of indicators decreases significantly – by 1,7-2,7 times in the second five-year plan (2016-2020). The highest level of variation in grain exports from the Black Sea region in 2016-2020 remains for corn – 19.2% (table 1, figure 3). The highest deviations in the supply of corn to the world market are shown by Bulgaria – 38,1% and Romania – 33,1%, while Ukraine and Russia have a variation rate of 24,5-24,8%, that shows more stable supplies from these countries.

The rate of variation for wheat from the Black Sea region is quite moderate – an average of 13,9%, with slightly higher rates of variation in Russia, Ukraine and Kazakhstan – 16,0-16,9%.

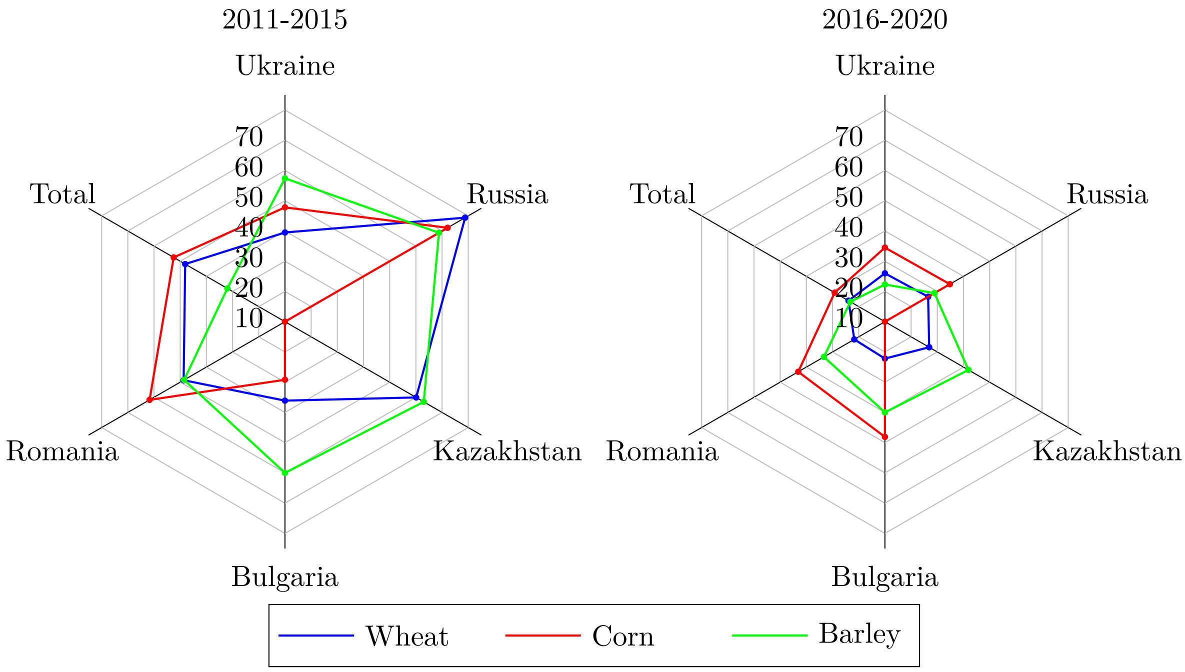

Figure 3. Coefficients of variation of export supplies of grain from the countries of the Black Sea region, 2011-2015, 2016-2020, %.

Kazakhstan and Bulgaria stand out for barley (30,0-31,9%), while Ukraine and Russia had a moderate variation (12,3-18,9%).

The coefficients of variation for the countries that are key exporters of the respective type of grain (wheat, corn, barley) were calculated for comparison. It turned out that the most stable suppliers of wheat to the world market were Canada and USA in 2016-2020, its coefficients of variation are in the range of 6,7-10,2% (table 1). Stable supply of corn is provided by the USA with a coefficient of variation of 11,1%, while Brazil and Argentina have the same variation of export indicators as Ukraine and Russia (23-25%). Ukraine shows the lowest scattering of export indicators for barley – 11,1% and the EU 13,0%, other countries have a significant variation of indicators (> 20%).

The influence on export supplies of various factors should be investigated in more detail to increase the stability of grain supplies from the Black Sea region to world markets, so as gross duties, transitional grain balances, exchange rate fluctuations, export restrictions, imperfect logistics, etc. These issues will be the subject of our further researches in the future.

Thus, the calculations allow us to state that the export activity of the countries of the Black Sea region gained more and more efficiency and stability in the studied period (2011-2020), which indicates the constant development of international relations between the countries that are suppliers and buyers of grain in the Black Sea region.

According to the long-term forecast of the International Grains Council (IGC), world grain trade will grow by 1,3% annually over the next few years. This expansion will be due to increased demand for grain in Asia and Africa because of 1) population growth and increasing popularity of grain and flour products 2) increasing demand for grain crops for feed purposes. Whether these forecasts will come true, taking into account the significant destruction of logistics chains in the Black Sea region, is an open question.

4.2. The impact of the war in Ukraine on trade and world prices
Ukraine held a leading position not only among exporters of the Black Sea region, but also among world exporters before the beginning of the war. Even in the 2021/2022 marketing year, it still managed to take fifth place among wheat exporting countries, third place among barley exporting countries and fourth place among corn exporting countries. The majority of Ukrainian products were exported by sea. The country had almost 3,000 kilometers of sea coast with 18 active ports, including 5 in the occupied Crimea. About 90% of Ukraine's grain export volume passed through sea corridors.

The invasion of Russian troops on the territory of Ukraine led to significant destruction of infrastructure facilities, including logistics chains. The presence of Russian troops in the Black Sea ports of Ukraine paralyzed the export of Ukrainian grain, oil, meal, etc. for five months. The established connections, which were built up over the years, were destroyed, and only starting from August 2022, the so-called 'grain corridor' became to operate that was only partially able to unload grain-filled elevators in Ukraine.

Immediately after the start of Russia's armed attack on Ukraine, agricultural markets around the world were shocked. Commodity prices flew up. In a situation of uncertainty, the demand for products increased, because market participants did not understand what could be expected in the near future. The volatility of wheat prices was higher than for other crops, because it is a food crop that is consumed by the population of the whole world. Futures for American wheat on the CME jumped by 60% compared to the pre-war period (figure 4). Futures prices for US corn also rose, but to a lesser extent – there are by 35%.

We cannot agree with the opinion of the authors Glauben et al [13]: "Currently there is no reason to panic buy or increase export controls on world grain markets in the coming marketing year, as markets appear to be calming".

In November 2022, wheat prices were 32% higher compared to the same period last year,

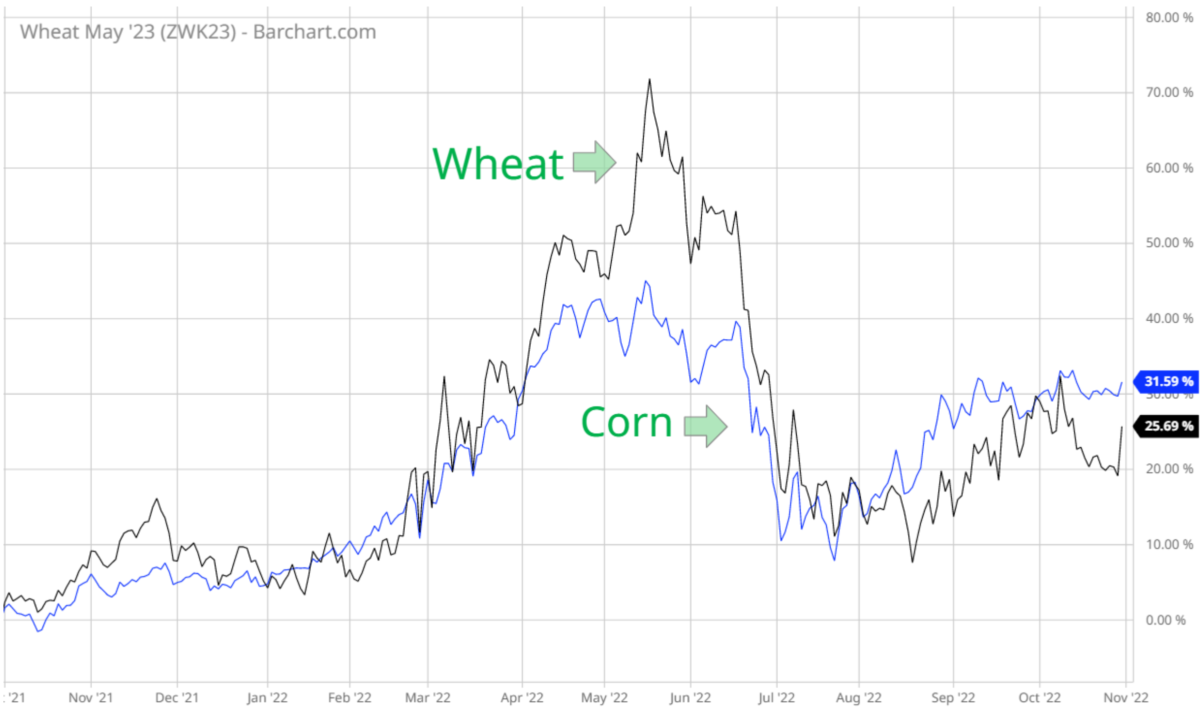

Figure 4. Chicago Board of Trade Wheat and Corn Price Growth Rates, November 2021 – November 2022.

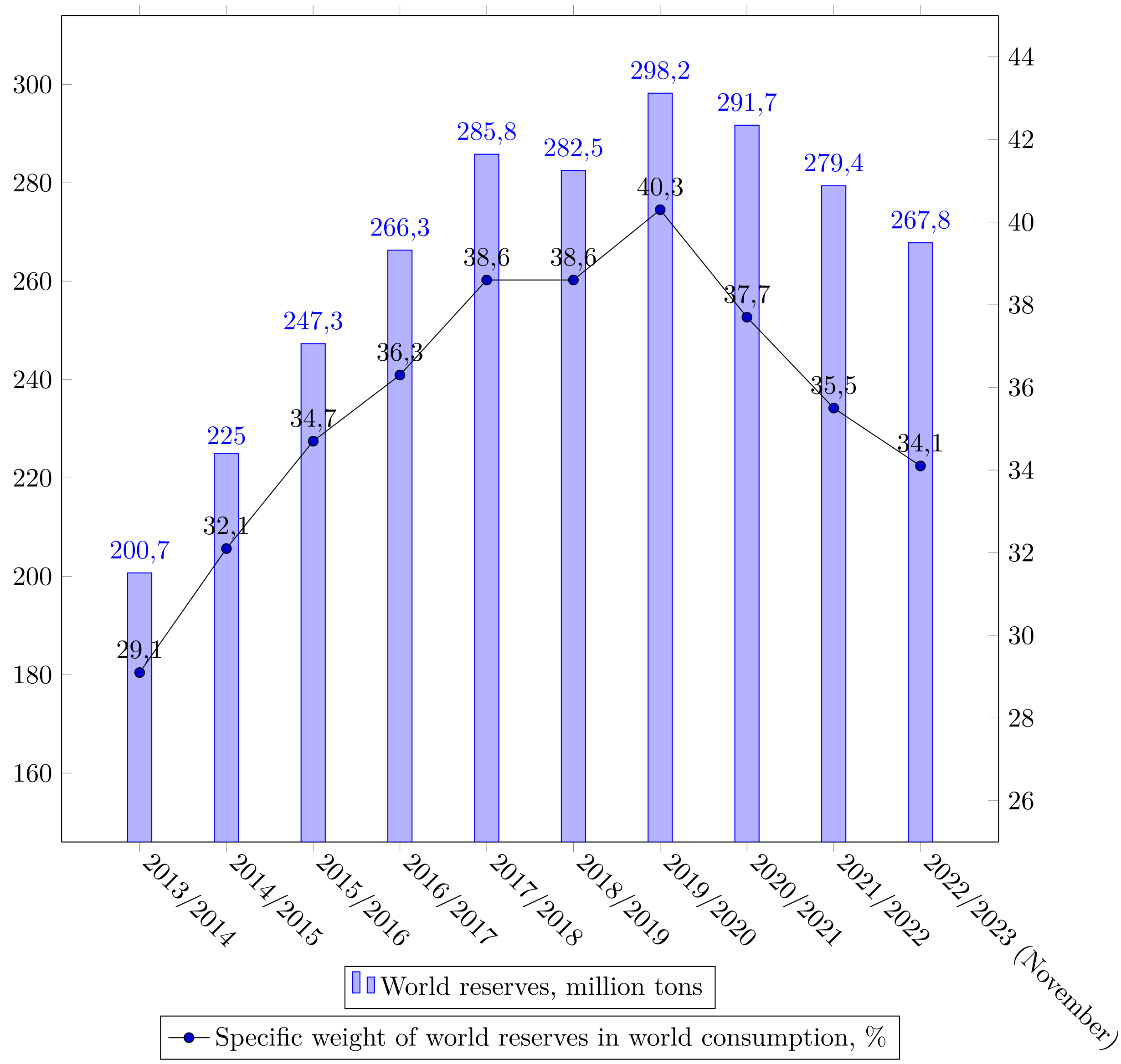

Figure 5. Specific weight of world reserves in world consumption in 2013/2014 – 2022/2023, %.

corn prices were also 26% higher. The world's temporary stocks of wheat are decreasing. Thus, as of November 2022, the indicator of the ratio of temporary stocks of wheat to its consumption calculated by us was 34.1% in the 2022/2023 marketing year (figure 5). Although this is not a critical level, it is the lowest level in the last 8 years [20]. A decrease in global wheat stocks will push prices higher in the future.

The inverse correlation between the level of prices and the level of product reserves was proved as early as the 17th century by the English economist Gregory King, who, using the example of the corn market, calculated the proportions of the correlations: the fall in the harvest and the corresponding increase in prices. In economic science, such a cause-and-effect connection was called the 'King effect' [21]. The reduction of reserves in the current marketing year will lead to another increase in exchange quotations for grain crops [22].

In 2022, Ukraine lost 30% of its wheat crop (−8 million tons), and 17% of its barley crop

(−1,1 million tons). In the fall of 2022, it was possible to sow only 61% of the wheat and 69% of the barley areas. That is, the capacity of the Ukrainian agricultural sector has significantly decreased. It is expected that 42% less Ukrainian wheat will be exported in the 2022/2023 marketing year than in the 2021/2022 marketing year [20]. The loss of grain export volumes from Ukraine will increase world prices in the future. This increase in prices will especially hurt poor countries, which are geographically and economically profitable to buy Ukrainian grain.

Consider the competitiveness of Ukraine in the world grain market under the conditions of Russia's military aggression. For this purpose, a SWOT matrix has been developed, which highlights Ukraine's competitive position on the world grain market (table 2).

Table 2. SWOT analysis of competitive position of Ukraine on the world grain market.

Strengths	**Weaknesses**
• Natural soil fertility, grain traditions • Geographical location, proximity of individual markets • Significant excess of production capacity over domestic needs • Competitive grain prices compared to the prices of other exporting countries • Cheap labor	• Insufficient use of new production technologies, modern equipment, etc. • Unstable legal and regulatory framework, lack of state support for grain producers and exports • Lack of opportunities for small and medium-sized businesses to hedge price risks on the stock exchange • "Bottlenecks" in the logistics of grain cargo • Insufficient quantity of grain of export quality
Opportunities	**Threats**
• Existing potential for growth of grain yields and, accordingly, increase of production (exports) • Interest of China, Africa, the Middle East and other countries in Ukrainian grain and opportunities to expand exports • Expansion of the Export Credit Agency, which has been operating de facto since 2021 • Forceful support of international organizations and some countries in the organization of grain supplies to the world market • Development of alternative logistics routes – transshipment of grain through ports or transportation by rail and road through the western borders	• Military and political instability due to Russia's military actions against Ukraine • The critical environmental situation in the war zone and other regions subject to shelling and bombing. In the post-war period, it will take years to restore disturbed ecosystems, in particular to restore soil fertility. • The activity of the operation of logistics routes in the Black Sea depends on international agreements (it is about the operation of the "grain corridor") • Continuation of the war may lead to further reduction of grain production in Ukraine • Global climate change, which is reducing (moving to the North) the area of favorable agriculture

The SWOT analysis shows that Ukraine has enough strengths and opportunities to expand grain supplies for export. All these opportunities will be realized under the conditions of the most outstanding end to the war and the restoration of normal business activities in the country.

Russia's aggression against Ukraine also threatens global food security [23]. The problem of hunger in the world and the tendency to increase the population on the planet is the reason that should motivate international organizations and individual countries to help Ukraine in restoring its vitality and restoring the stability of export grain supplies to the world market and, accordingly, the sustainability of the development of the Black Sea region.

5. Conclusions and outlook

So, research has shown an increase in the share of the Black Sea region in the supply of grain to the world market before Russia's military invasion of Ukraine. Thus, the countries of the Black Sea basin have provided a third of world wheat exports, a quarter of world exports of corn and 40% of barley on average in 2016-2020. The leaders of this region were Ukraine and Russia. With less experience than traditional players in the international market, the Black Sea countries have shown a fairly steady development of grain export trade in recent years, as evidenced by our calculated coefficients of variation. Thus, comparing the uniformity of grain supply to the world market in 2016-2020, we found that the Black Sea basin provided a higher level of stability of wheat exports than the EU and Australia and the stability of corn supplies from this region at the level of Argentina and Brazil. The most stable suppliers of corn to the world market were the United States, wheat – Canada and the United States, barley – Ukraine. The indicators which were calculated by us confirm the increasing efficiency and sustainability of the development of the Black Sea region in the pre-war period. However, the war started by Russia, destroys the established economic relations between the countries, blocks the arrival of crops from Ukraine, while some countries are in great need of these products.

Because of the complete or partial blockade of Ukrainian ports, the world market did not receive a significant part of the products, which had influence on world prices. With the beginning of the armed aggression, stock exchange quotations for wheat and corn jumped by 60% and 35%, but even after 8 months from the start of the war, they still exceed last year's level, by 32% and 26%, respectively.

Regarding the prospects for the development of export trade from Ukraine: the results of the SWOT analysis confirm the sufficient competitiveness of country. However, a significant number of threats are also present. The best solution to this issue and the elimination of most "threats" is a complete cessation of hostilities and the withdrawal of troops from Ukrainian territories and waters. The restoration of full-fledged business activity of Ukraine, as one of the key players in the world grain market, will allow to restore the sustainable development of world trade and global food security.

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References

[1] FAO, IFAD, UNICEF, WFP and WHO 2020 *The State of Food Security and Nutrition in the World 2020. Transforming food systems for affordable healthy diets* (Rome: Food and Agriculture Organization) URL https://doi.org/10.4060/ca9692en
[2] Götz L, Glauben T and Brümmer B 2013 *Food Policy* **38** 214–226 URL https://doi.org/10.1016/j.foodpol.2012.12.001
[3] Zyukin D A, Zhilyakov D I, Bolokhontseva Y I and Petrushina O V 2020 *Amazonia Investiga* **9**(28) 320–329 URL https://doi.org/10.34069/AI/2020.28.04.36
[4] Svanidze M and Götz L 2019 *Global Food Security* **21** 60–68 URL https://doi.org/10.1016/j.gfs.2019.07.004

[5] Berezhnoy V I, Martseva T G, Berezhnaya E V, Berezhnaya O V and Tolmachev A V 2021 *Revista Geintec-Gestao Inovacao e Tecnologias* **11**(4) 980–996 URL http://web.archive.org/web/20230311074953if_/http://www.revistageintec.net/wp-content/uploads/2022/03/2162.pdf
[6] Kozachenko D M, Vernigora R V and Rustamov R S 2017 *Science and Transport Progress. Bulletin of the Dnipropetrovsk National University of Railway Transport* **2(68)** 56–70 URL https://doi.org/10.15802/stp2017/99952
[7] Heigermoser M, Götz L and Jamali Jaghdani T 2019 Driving Black Sea grain prices: Evidence on CBoT futures and exchange rates *Proceedings of the NCCC-134 Conference on Applied Commodity Price Analysis, Forecasting, and Market Risk Management* (Minneapolis, USA)
[8] Gafarova G, Perekhozhuk O and Glauben T 2015 *Journal of Agricultural and Applied Economics* **47**(3) 287–316 URL https://doi.org/10.1017/aae.2015.16
[9] Goychuk K and Meyers W H 2014 *Canadian Journal of Agricultural Economics/Revue canadienne d'agroeconomie* **62** 245–261 URL https://doi.org/10.1111/cjag.12025
[10] Kvasha S, Pankratova L, Koval V and Tamošiūnienė R 2019 *Intellectual Economics* **13**(2) 195–209 URL https://doi.org/10.13165/IE-19-13-2-10
[11] Sanders D 2021 *Southeast European and Black Sea Studies* **21**(3) 415–436 URL https://doi.org/10.1080/14683857.2021.1935771
[12] Berkhout P, Bergevoet R and van Berkum S 2022 A brief analysis of the impact of the war in Ukraine on food security Policy Document 2022-033 Wageningen Economic Research URL https://doi.org/10.18174/568027
[13] Glauben T, Svanidze M, Götz L, Prehn S, Jamali Jaghdani T, Đurić I and Kuhn L 2022 *Intereconomics* **57**(3) 157–163 URL https://doi.org/10.1007/s10272-022-1052-7
[14] FAO 2022 The importance of Ukraine and the Russian Federation for global agricultural markets and the risks associated with the current conflict Information Note 8 March 2022 Food and Agriculture Organization URL https://www.fao.org/3/cb9236en/cb9236en.pdf
[15] FAO 2022 The importance of Ukraine and the Russian Federation for global agricultural markets and the risks associated with the war in Ukraine Information Note 10 June 2022 Update Food and Agriculture Organization URL https://www.fao.org/3/cb9013en/cb9013en.pdf
[16] United Nations 2022 UN Comtrade URL https://comtradeplus.un.org/
[17] 2023 USDA Foreign Agricultural Service URL https://fas.usda.gov/
[18] 2023 AgriSupp URL https://agrisupp.com/en/
[19] Abdildin N K and Mizanbekov I T 2017 Grain logistics in the development of Kazakhstan's export strategy *Nikon readings* 22 pp 393–396
[20] United States Department of Agriculture Foreign Agricultural Service 2023 Grain: World Markets and Trade URL https://apps.fas.usda.gov/PSDOnline/Circulars/2023/07/Grain.pdf#navpanes=0
[21] Yule G U 1915 *Journal of the Royal Statistical Society* **78**(2) 296–298 URL https://doi.org/10.2307/2340610
[22] Pankratova L 2017 *Ukr. socium* **3(62)** 77–86 URL https://doi.org/10.15407/socium2017.03.077
[23] UN GCRG 2022 Global impact of the war in Ukraine: Billions of people face the greatest cost-of-living crisis in a generation Brief 2 UN Global Crisis Response Group on Food, Energy and Finance

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Land resource management system in the sustainable development context: scientific and practical approaches

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Abstract. One of the main domestic and foreign policy principles of Ukraine is the preservation of the environment and its components, which is vital for the human existence, his current and future generations. It was found that the amount of land resources available at our disposal is limited, therefore it requires sustainable management. This calls for recognition of raising awareness importance of the rate at which humans are depleting and destroying land resources. This formed a new paradigm about the role and importance of land management and land use. The purpose of the study is to identify the factors that have the greatest impact on the spread of soil degradation and pollution, and to identify priority environmental measures in the land management system, specifically offers for land conservation, reduced land areas with the use of pesticides and agrochemicals, which would improve the state of agro and ecosystems, would create conditions for the restoration of biodiversity in the agro sphere, would contribute to the prevention of soil degradation and contamination by chemical substances. Implementation of the provided measures is aimed at improving the quality of the natural environment and human living conditions. The indicators dependence of agricultural land use and production intensification factors was revealed through economic and mathematical modeling.

1. Introduction

Land resources are the main component of Ukraine's natural resource potential. Therefore, the concentration of large tracts of land in different types of landowners and land users can become a factor that will cause changes in the nature of use in the country and its regions, affect their social and economic development and the environment condition. The nature of land resources usage affects almost all spheres of social and economic regional development of different levels, in particular territorial communities, the condition and quality of agricultural lands, determines the nature of anthropogenic impact on the environment. By endorsing the Sustainable Development Goals, the global community, including Ukraine, reaffirmed its commitment to sustainable and inclusive economic growth, social inclusion, environmental protection and the development of peaceful, just and inclusive societies through a new global partnership. The result of this work was the national SDG (Sustainable Development Goals) system of the Central Development System, which consists of national development tasks with corresponding indicators [1]. All these goals can still be achieved. As the UN Secretary-General's report states: "The choices we make or don't make today can lead to further destruction or breakthroughs to a greener, better and safer future". [2].

Implementation of sustainable development principles requires the formation of development directions strategic vision based on a new philosophy of thinking and new aspects of political activity. The transition to the principles of sustainable development will require comprehensive structural changes in the management of land resources. That is, the management of land resources is key to achieving the goals of sustainable development, ensuring food security, jobs and income in the long term. In this paradigm, the concept of sustainable management of land resources appeared, which means the use of land resources, including soil, water, animals and plants, for the production of goods to meet changing human needs while simultaneously ensuring the long-term productive potential of these resources and preserving their ecological functions. Increasing investments in sustainable management of land resources can significantly contribute to achieving the Sustainable Development Goals Goal 1 (overcoming poverty in all its manifestations), Goal 2 (overcoming hunger, achieving food security, promoting the balanced development of agriculture), Goal 6 (ensuring accessibility and balanced use water resources), Goal 13 (fighting climate change and its consequences) and Goal 15 (ensuring the protection and restoration of terrestrial ecosystems and promoting their balanced use; implementing balanced forest management; fighting desertification; stopping the process of land degradation and starting their restoration and halting the loss of biodiversity). Thus, ensuring the continued integration of sustainable land management into all state and local programs is a safe investment that ensures better sustainability for all, not only in the country, but in a land-degradation-neutral world.

Effective management of land resources is one of the most important conditions for the development of the state and territorial communities in Ukraine. Over the past decades, almost all issues important for the sustainable development of land relations have been regulated at the legislative level: maintaining a land cadastre, registering rights to real estate, carrying out land management and land valuation [3].

2. Literature review

Problematic aspects of ecological character in the system of land resources management in the sustainable development context, features of rational nature management in the field of agriculture are studied by number of authors [4–10].

Koshkalda et al [5] considered aspects regarding by the need to solve the research and technical problem of providing information support for the assessment of the state of land resource mapping and their management using modern geoinformation technologies, the development and optimization of interconnected algorithms and programs. Used an integrated land cover classification method targeting low-accuracy regions on large-scale maps. Low-accuracy areas can be detected by estimating the accuracy of the data with a moderate resolution spectroradiometer. This method optimizes the entire classification process, including image selection, as well as the classification algorithm and features. An optimal algorithm of classification and features for various regions with low accuracy is proposed, which can be used in the process of regulation and management of land relations.

Tretiak et al [8] claims that today in Ukraine, land (in the form of land use) is not considered at the government level as a terrestrial biologically productive system, which includes soil, vegetation, other biomass, as well as ecological and hydrological processes that occur within this system. According to this the state and quality of land use is not associated with a complex of security threats to human life.

Dombrovska et al [11] considered Remote Earth Sensing, which makes it possible to obtain data on dangerous, hard-to-reach objects and places, and also allows for operational monitoring of large areas of the terrain. The use of modern methods of obtaining data from remote sensing of

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the earth has significantly expanded the horizons of using such data, their analysis, interpretation and modelling of a wide range of natural processes and human activities. Today, the possibilities of obtaining remote sensing data of the Earth by modern methods, both space and UAV, channel combinations, image visualization indices in combination with geoinformation technologies solve some scientific, practical and economic problems that are already used in industry cadastres.

One of the ecological economy founders, Herman Daly, claims that the human-made economy is “embedded” in the ecological global system. Quality indicators of the environment are determined by the quality of atmospheric air, the quality of agricultural land, the quality of surface water and the quality of biotic resources [12].

Scientific views on the sustainable management system of land resources and soil fertility are actively covered in foreign publications.

Lecarte and Negre [13] provides an overview of the effect of the decline in the number of farms across the EU on the European farming model (EFM), which is built around the notion of multifunctionality and provision of public goods by agriculture. It concludes that in order to foster sustainability and resilience, the EFM and policy tools must embrace the emerging diversity of farmer profiles and stimulate socially desirable adaptive strategies that preserve the multifunctionality of farming.

Rosário et al [14] presents a systematic literature review focused on the use of sociopsychological determinants to understand the adoption of sustainable agriculture innovations, combining conventional bibliometric analysis with the method of vote-count. This method enabled an evaluation of the ability of the determinants considered by the models, as well as respective sociopsychological constructs, to explain the innovation adoption. Our results show a significant growth in the research employing theory and models built on sociopsychological factors to understand the decision-making processes undertaken by farmers in the context of the adoption of sustainable agriculture innovations. The development of statistical models and techniques, such as the structural equation model (SEM), has facilitated the inclusion of a growing set of sociopsychological variables. However, our review highlights that the selection of the sociopsychological constructs used by research to explain farmers’ adoption of sustainability innovations relies mainly on constructs defined for other decisional contexts, such as the adoption of innovations by firms in other sectors.

Anderson et al [15] develops a framework for advancing agroecology in transformations towards more just and sustainable food systems focusing on power, politics and governance. It explores the potential of agroecology as a sustainable and socially just alternative to today’s dominant food regime.

The analysis by Migliorini et al [16] has been partly based on results of a dedicated literature search and partly on grey literature and expert knowledge. After an overview of the history of agroecology, targeted research and education, collective action(political and social), and some agroecological practices in the three countries are presented. These countries share a rather similar use of the term “agroecology”, but they differ regarding(i) the existence/extent of strong civil and social movements; (ii) the type of study/educational programmes, and the relative importance of different scientific disciplines and their evolution; (iii) the development of political support and legal frameworks; and (iv) the elaboration of concepts to rediscover traditional practices and apply new ones, often taken from the organic agriculture sector. Agroecology is an emerging concept for the Mediterranean agricultural sector, with huge potential due to the peculiar socio-cultural, bio-physical, and political-economic features of the region. To boost agroecology in Mediterranean Europe, better networking and engagement of different actors within a coherent institutional framework supporting the transition is strongly needed.

3. Results and discussion

Nowadays, Ukraine's land resources, especially agricultural lands, are subject to significant transformation as a result of human activity. The main factor of transformation is the plowing of soils and their intensive use in agriculture. Lands with fertile soils and geomorphological conditions favorable for agriculture underwent the greatest transformations.

The increase in agricultural development of land resources, which is accompanied by an increase in plowing of land, indicates an increase in the anthropogenic load on a unit of land area, geological imbalance, and the development of soil erosion (figure 1).

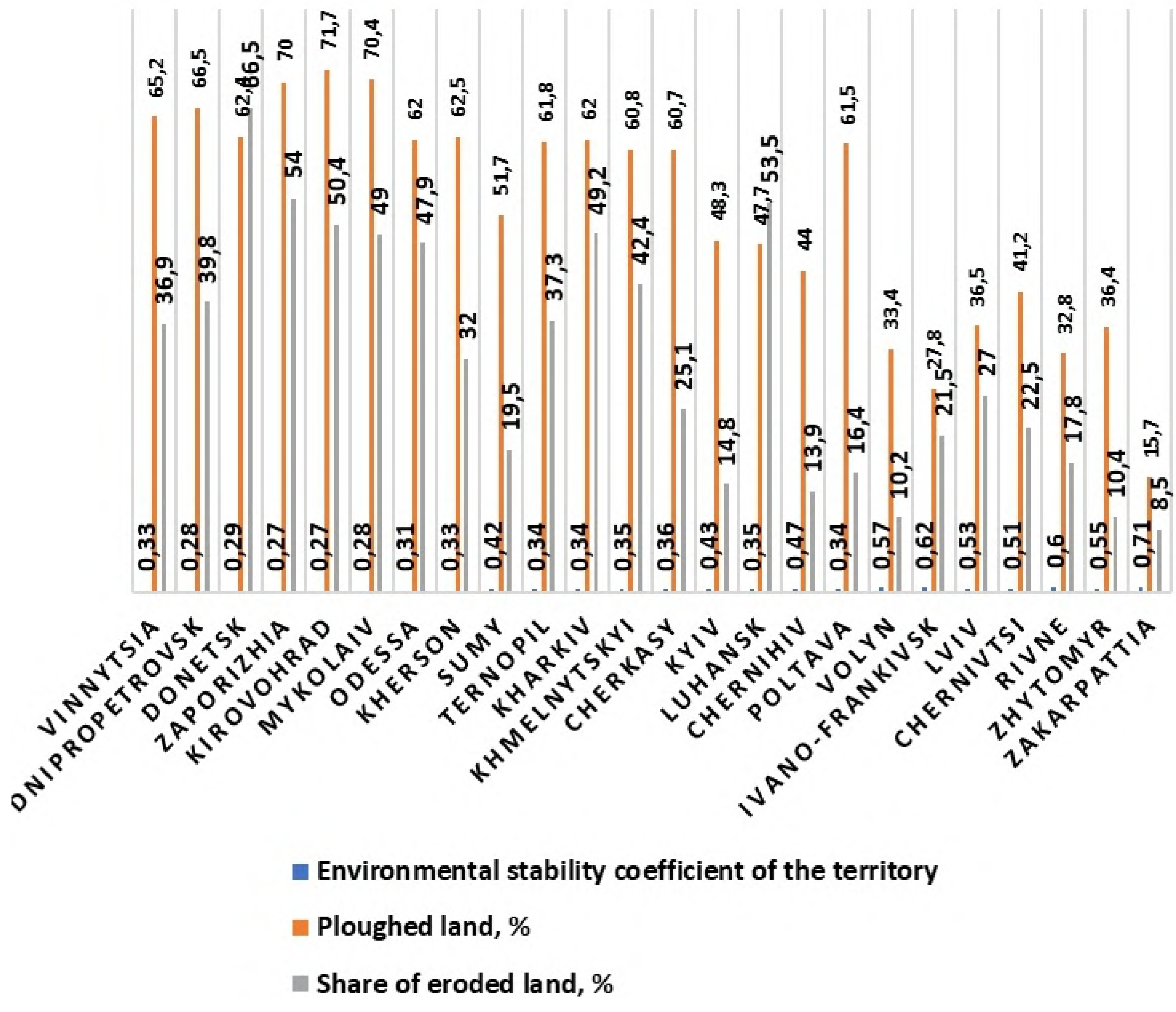

Figure 1. Ecological balance indicators of territorial units of Ukraine.

According to the scientists' methodology of the Land Management Institute of the Ukrainian Academy of Sciences, the coefficient of ecological stability indicates that: less than 0.33 – the territory is ecologically unstable; from 0.34 to 0.50 – refers to steady unstable; from 0.51 to 0.66 – passes into the limits of average stability; if it exceeds 0.66, the territory is ecologically stable. Figure 1 shows that most regions of the country have an ecologically unbalanced and vulnerable territorial structure, which is associated with high plowed land. Only Zakarpattia Oblast has an ecologically balanced territory. There is a direct relationship between land erosion and the degree of ecological stability.

The dependence of agricultural land use indicators and factors of production intensification is most accurately determined by economic and mathematical modeling in the form of a multifactorial regression equation (using the example of agricultural enterprises of the Krasnokut Territorial Community of the Bogodukhiv District of the Kharkiv Region). On the basis of the multivariate regression of the 1st degree, the relationship between the value of gross production (Y) and the area of arable land (X_1), qualitative assessment of arable land (X_2), production costs (X_3), and the cost of fixed and working capital (X_4) was revealed. The dependence obtained as a result of data processing is characterized by the equation:

$$Y = -2828.28 + 0.75X_1 + 59.89X_2 + 0.17X_3 + 0.10X_4$$

To assess the adequacy of the accepted mathematical model, we use Fisher's test.

The values of the equation parameters give reason to note that with an increase in the cost of fixed and working capital and the quality of land, the cost of gross production increases by 0.10 UAH and 59.8 thousand UAH, respectively. An increase in the area of arable land and production costs in farms contributes to an increase in the value of gross products by 0.75 UAH and 0.17 thousand UAH.

There is a fairly close relationship between the effective and factor characteristics (correlation coefficient is 0.8743). The test for significance proves the presence of a non-random dependence, as well as a high level of adequacy of the model construction (the actual F test of $F(3.26) = 8.93$).

Analysis of standardized beta coefficients showed that the cost of fixed production and working capital has the greatest influence on the cost of gross production ($\beta_4 = 0.688$), the next indicator is the arable land area ($\beta_1 = 0.595$), and then production costs ($\beta_3 = 0.326$), point of qualitative assessment of arable land ($\beta_2 = 0.220$).

An important issue today is the improvement of the legal, economic and ecological mechanism for the removal (conservation) of degraded, unproductive and man-made agricultural lands from intensive use. The legal basis for conservation of degraded and unproductive lands are defined by the Land Code of Ukraine [17, articles 171–172] and the Law of Ukraine "On Land Protection" [18, article 51]. The order of land conservation [19] defines the organizational principles of conservation of degraded, unproductive and technogenically polluted lands, reference indicators characterizing soil properties and determining the need for land conservation in natural-agricultural zones. But nowadays, a clear methodology for ensuring its implementation has not been defined. Therefore, it is necessary at the legislative level, with the participation of specialized scientific institutions, to develop a methodology for land conservation.

State and regional programs are adopted for the purpose of conducting soil surveys, protection, rational, ecologically safe use of soils, preservation and reproduction of their fertility. The implementation of state target programs in the field of reproduction, improvement and protection of soil fertility is an integral part of agrarian policy and a decisive factor in ensuring the sustainable development of our country.

Land conservation, regardless of the form of ownership, is carried out according to the working project of land management on land conservation, which defines the types, methods of land conservation, the term of conservation, directions of land use [19].

In order to implement the goals of sustainable development of both the state as a whole and territorial communities (Goal 15 – ensuring the protection and restoration of terrestrial ecosystems and promoting their balanced use; carrying out balanced forest management; combating desertification; ending the process of land degradation, restoring and stopping loss of biodiversity), we developed offers for the conservation of degraded and unproductive lands of the Krasnokut territorial community of the Bogodukhiv district of the Kharkiv region.

Taking into account the indicators that characterize the soil properties and determine the need for land conservation in natural and agricultural zones, it is offered to apply the following directions of conservation:

Erodibility (eroded and deflated). These are lands with moderately and strongly eroded and eroded soils, outcrops of soil-forming and underlying rocks. It is planned to remove from the arable land and further lime and use it for onion pasture lands with standardized livestock grazing or afforestation. Medium and strongly deflated soils are subject to removal from agricultural land by afforestation.

The most disturbed lands with rock outcrops, washed-out and heavily washed soils, these lands should be removed from the arable lands with lime or afforestation. In the Krasnokut community, the area of such lands is 176 hectares (agro-production groups 57d, 57e, 51e, 51g, 51e). Medium-washed soils on complex slopes of more than 3–5° are also subject to transformation into pasture lands, approximately 1560,9 hectares are allocated for pastures, 176.3 hectares for afforestation. On other lands with moderately washed soils, it is advisable to carry out rehabilitation. Conservation-rehabilitation of agricultural lands is planned by allocating them or transferring them to fallows and using them as hayfields and pastures for a period of 10 to 20 years with subsequent return for agricultural use. The area of these lands is 6,824.3 hectares.

Soils of light mechanical composition. These are sandy and clayey-sandy soils. They are permanent centers of deflation. From an economic point of view, the impracticality of their use is due to the inadequacy of costs for maintaining a sufficient level of their fertility, the profit obtained from the harvest. The conservation of these lands is irreversible, that is, they must be removed from the agricultural lands with subsequent afforestation. In the community, this is land on an area of 8.0 hectares (agro-production group 1 a).

Soil salinity. This category of lands is represented by salt marshes, medium and highly saline mainly hydromorphic soils (meadows, swamps), as well as secondary saline soils. Saline soils of natural origin are removed for haying or renaturalized (regeneration) without human intervention. Secondary salinized soils are taken for temporary conservation with subsequent return to the composition of arable lands, if the indicator of the groundwater level is reduced below the critical level and desalination. In the Krasnokut community, this category of land is 133.0 hectares (agro-production groups 141,142', 143', 144', 134'd, 134 e), it is offered to allocate 66.5 hectares for haymaking, and 66.5 hectares to be renaturalized without human intervention.

Salinity. These are medium and highly saline soils. Directions for use are the same as the previous group. These are lands (agro-production groups 165 d, 165 e) on area of 30.0 ha, which should be converted into hay fields.

Waterlogging and swamping. This category includes lands with meadow and sod-podzolic soils, as well as sod-clay, mineral and organic bog soils. These lands must be naturally renaturalized. It practically does not require any expenses, because good watering ensures their quick settlement with natural fauna and flora, adaptation to the surrounding environment. The area of these lands is 266.0 hectares (agro-production groups 176 b, 176 c, 209 c, 209 g, 209 d, 209 e, 209 l, 208 d, 208 e).

Offers for the conservation of degraded and unproductive arable lands by types of degradation and ecologically appropriate directions of their use are given in the table 1.

Removal of degraded and unproductive lands from intensive cultivation will allow: 1) to concentrate investments on more fertile lands and obtain a higher yield of agricultural crops on them; to increase the level of the fodder base development and, on their basis, the livestock industry; 2) to reduce the rate of erosion processes development and further soil degradation; 3) to bring the plowed percentage of the territory of the Krasnokut territorial community of the Bogodukhiv district of the Kharkiv region to 52% (actual ploughed 60.3%).

One of the necessary and determining prerequisites for the development of the land resources management system in the context of sustainable development is the application of the latest technical and technological achievements in the field of protection and reproduction use of land resources. This form of innovative activity in land resources management was reflected, in

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Table 1. Offers for the conservation of degraded and unproductive arable lands of the Krasnokut territorial community of the Bogodukhiv district of the Kharkiv region.

Degradation types	Area, hectares		Conservation					
	total	%	rehabilitation	conversion				regeneration
				total	hayfield	pasture	forest	
Eroded and deflated	8737.5	95.2	6824.3	1913.2	176.0	1560.9	176.3	–
Soils of light mechanical composition	8.0	0.08	–	8.0	–	–	8.0	–
Soil salinity	133	1.4	–	133.0	66.5	–	–	66.5
Salinity	30.0	0.5	–	30.0	30.0	–	–	–
Waterlogging and swamping	266.0	2.8	–	–	–	–	–	266.0
Total	9174.5	100	6824.3	2084.2	272.5	1560.9	184.3	332.5

particular, in the implementation of the following directions in economic practice: resource-saving technologies in agriculture, the use of remote land sensing data (RSD), GIS technologies, the role of soils in the process of mitigating the consequences of climate change, agroforestry, etc.

Precision agriculture is characterized by the automation of applied methods, in particular, yield registration with continuous monitoring. This management practice is available mainly to large commodity producers of agricultural products, but it is also recommended for small farms. The main obstacles to the wide implementation of precision agriculture are the lack of skills of working with databases and automated decision support systems among business entities [20].

GIS ensures the practical implementation of non-zero risk concept in the land resources management as an ecological and economic system. The concept recognizes the fact that absolute security is insufficient and requires not only the study of factors and sources of increased risk, but also the forecast of the development of events and the assessment of their consequences [21]. By predicting the probability of certain events and the expected amount of profit (losses), investigating alternative solutions, they make the optimal management decision regarding the use of land resources. RSD and GIS data allow solving the following tasks in agriculture, particularly: mapping and inventory of agricultural lands; monitoring and control in crop production; state of crops, evaluation of crop emergence, degree of ripening, damage by pests/diseases; yield forecasting; monitoring and control of pastures and hayfields in animal husbandry; monitoring and control of reduction or loss of soil productivity, degradation, water and wind erosion, salinization, flooding, etc.

In the latest practice of sustainable land resources management, agroforestry is spreading, which allows economic activities to be carried out with the preservation of biodiversity, greening of agriculture and industrial landscapes. Agroforestry reduces the anthropogenic load on natural forests, creates a habitat for native species of plants and animals, and also promotes effective land use in fragmented landscapes [20]. The use of agroforestry methods allows obtaining not only a positive economic effect of increasing the biological productivity and sustainability of agro and forest ecosystems, but also a significant ecological effect.

In order to preserve and reproduce the productivity potential of arable land, the practice of organic and no-till farming are becoming widespread.

Increasing the resilience of agricultural production to climate change, especially in the south of Ukraine, in the areas most affected by drought, requires the expansion of irrigated areas and the restoration of irrigation infrastructure. According to official statistical data, there are 5.48 million hectares of reclaimed land in Ukraine, including 2.17 million hectares of irrigated land and 3.3 million hectares of drained land with appropriate land reclamation infrastructure (reservoirs, main and distribution channels, protective dams, pumping stations, pipelines, pools of daily regulation, collector and drainage network and other hydrotechnical structures and objects). During the last time, about 550,000 hectares of agricultural land were actually irrigated, and bilateral regulation was carried out on the area of about 250,000 hectares. Agricultural producers who use irrigation can increase yields by 30-50%, depending on the crop. The irrigation and drainage infrastructure of the water management and melioration complex was built in the 1960s and 1990s, and today it is in critical condition, especially the intra-farm network. Today, there is no reliable and systematic information about the technical condition of engineering infrastructure objects and the operation of reclamation systems, distribution by owners and water users, location, etc. This makes it difficult to make effective management decisions regarding their use, modernization and restoration. Preliminary calculations and expert assessments indicate that, if the current rate of increase in the deficit of natural moisture supply of the country's arable lands is maintained, by 2050, about 3 million hectares of arable land in the southern regions will be unsuitable for commercial agrarian production of plant products [22]. As a result, and taking into account the tendency of dehydration in the central and northern regions of the country, the gross production of grain (with modern resource supply of agricultural technologies) may decrease by 20-25% or 14-18 million tons.

4. Conclusions

The modern land management system should encourage agricultural enterprises and other interested parties to take decisive action in solving the problems of preserving valuable soil and black soil (chernozem) resources of Ukraine, to economical use and reproduction of their fertile potential. It is necessary to observe legality in the process of land use and land circulation, to promote the involvement of local territorial communities in solving priority problems related to the effective and ecologically safe use of soil resources and the reproduction of their fertile potential, to direct their activities to the improvement of the regulatory and legal framework on the problems of soil conservation, their effective use and reproduction of their fertile potential.

The main ecological directions in the land resources management system should be the following: ensuring the priority of environmental safety requirements in the use of land resources over economic interests; implementation of agrotechnical measures aimed at improving soil fertility and recovery; increasing the share of organic production; strengthening control over illegal plowing of pastures and water protection areas; restoration of forest strips; increase in investments in agriculture; use of modern resource-saving technologies, in particular, resource-saving no-till technology, which allows increasing soil moisture retention, improving water availability, and reducing soil erosion; application of organic fertilizers, in particular, manure, straw, residues of agricultural production; application of remote sensing data and GIS technologies.

In order to ensure sustainable development in the face of climate change and reduce greenhouse gas emissions in Ukraine, it is necessary to start work on the restoration of irrigation systems, form the structures of sown areas with the introduction of resource-efficient technologies for growing drought-resistant varieties and hybrids of agricultural crops.

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References

[1] President of Ukraine 2019 Pro Tsili staloho rozvytku Ukrainy na period do 2030 roku URL https://zakon.rada.gov.ua/laws/show/722/2019#Text
[2] UNICEF Office in Ukraine and Office of the United Nations Coordinator in Ukraine 2022 Sustainable Development Goals Ukraine 2021 Monitoring Report URL https://ukrstat.gov.ua/csr_prezent/2020/ukr/st_rozv/publ/SDGs%20Ukraine%202021%20Monitoring%20Report%20engl.pdf
[3] 2019 Efektyvne upravlinnia zemelnymy resursamy: konferentsiia Svitovoho banku URL https://rdo.in.ua/news/efektyvne-upravlinnya-zemelnymy-resursamy-konferenciya-svitovogo-banku
[4] Burliai A, Burliai O, Revutska A, Smolii L and Klymenko L 2021 *Agricultural and Resource Economics: International Scientific E-Journal* **7** 96–114 URL https://doi.org/10.51599/are.2021.07.01.06
[5] Koshkalda I, Vynohradenko S, Kulbaka V and Steshchenko D 2022 Features of land cover mapping in the low-accuracy areas on large-scale maps for land management *GeoTerrace-2022: International Conference of Young Professionals* (European Association of Geoscientists & Engineers) URL https://doi.org/10.3997/2214-4609.2022590057
[6] Dobriak D S, Budziak V M and Budziak O S 2013 *Ekonomika Ukrainy* (7) 83–94 URL http://nbuv.gov.ua/UJRN/EkUk_2013_7_8
[7] Kuryltsiv R, Hernik J and Kryshenyk N 2018 *Acta Sci. Pol. Formatio Circumiectus* **17**(2) 105–115 URL http://web.archive.org/web/20200214030826if_/http://www.formatiocircumiectus.actapol.net/pub/17_2_105.pdf
[8] Tretiak A M, Tretiak V M, Priadka T M, Kapinos N O and Lobunko Y V 2022 *Ahrosvit* (1) 3–12 URL https://doi.org/10.32702/2306-6792.2022.1.3
[9] Tretiak A, Tretiak V, Priadka T, Tretiak R and Kapinos N 2021 *Agrosvit* (20) 14–21 URL https://doi.org/10.32702/2306-6792.2021.20.14
[10] Khodakivska O V 2015 *Ekolohizatsiia ahrarnoho vyrobnytstva* (Kyiv: NNTs IAE)
[11] Dombrovska O, Hoptsii D, Kulbaka O, Siedov A and Surkova V 2022 Modern capabilities of obtaining remote sensing data as an integral tool for maintaining industry cadastres *GeoTerrace-2022: International Conference of Young Professionals* (European Association of Geoscientists & Engineers) URL https://doi.org/10.3997/2214-4609.2022590063
[12] Nesvietov O O 2001 *Visnyk Sumskoho derzhavnoho ahrarnoho universytetu* (Spetsialnyi vypusk "Ekolohichni problemy vyrobnytstva ta spozhyvannia ekolohichno chystoi produktsii") 356–359
[13] Lecarte J and Negre F 2022 Research for AGRI Committee - The Future of the European Farming Model: Socio-economic and territorial implications of the decline in the number of farms and farmers in the EU URL http://www.europarl.europa.eu/RegData/etudes/ATAG/2022/699621/IPOL_ATA(2022)699621_EN.pdf
[14] Rosário J, Madureira L, Marques C and Silva R 2022 *Agronomy* **12**(11) 2879 URL https://doi.org/10.3390/agronomy12112879
[15] Anderson C R, Bruil J, Chappell M J, Kiss C and Pimbert M P 2020 *Agroecology Now! Transformations Towards More Just and Sustainable Food Systems* (Cham: Palgrave Macmillan) URL https://doi.org/10.1007/978-3-030-61315-0
[16] Migliorini P, Gkisakis V, Gonzalvez V, Raigón M D and Bàrberi P 2018 *Sustainability* **10**(8) 2724 ISSN 2071-1050 URL https://doi.org/10.3390/su10082724
[17] Verkhovna Rada of Ukraine 2002 The Land Code of Ukraine URL https://zakon.rada.gov.ua/laws/show/2768-14?lang=en#Text
[18] Verkhovna Rada of Ukraine 2003 On Land Protection URL https://zakon.rada.gov.ua/laws/show/962-15?lang=en
[19] Cabinet of Ministers of Ukraine 2022 Pro zatverdzhennia Poriadku konservatsii zemel URL https://zakon.rada.gov.ua/laws/show/35-2022-%D0%BF#Text
[20] United Nations Environment Programme 2007 Global Environment Outlook 4 (GEO-4): Environment for Development URL https://wedocs.unep.org/20.500.11822/7646
[21] Ibatullin S I *et al.* 2012 *Mekhanizmy upravlinnia zemelnymy vidnosynamy v konteksti zabezpechennia staloho rozvytku* (Derzhavna ustanova Instytut ekonomiky pryrodokorystuvannia ta staloho rozvytku Natsionalnoi akademii nauk Ukrainy)
[22] 2022 Natsionalna dopovid pro stan navkolyshnoho pryrodnoho seredovyshcha v Ukraini u 2020 rotsi URL https://mepr.gov.ua/wp-content/uploads/2022/10/Natsionalna-Dopovid-2020-2.pdf

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The predictive and search system of amber (PSSA) and sustainable development of mining areas

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The predictive and search system of amber (PSSA) and sustainable development of mining areas

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Abstract. A new (“amber”) branch of the economy is currently developing in Ukraine, which includes the search for, mining and processing of amber. Ukrainian amber is noted for its high quality and is one of the most competitive types of domestic coloured stones on world markets. A significant part of the territory of Ukraine is promising for the discovery of placer deposits of amber, but their industrial development is currently carried out only within the boundaries of “the Pripyat amber-bearing basin” (PAB), which covers the regions of Volyn, Rivne, Zhytomyr, and Kyiv regions. The development of the “amber” industry of Ukraine caused problems of a production, organizational, socio-economic and environmental nature. They significantly influence the socio-economic development of amber mining areas. These are: 1) lack of a national program for the development of the “amber” industry; 2) its insufficient level compared to the real potential; 3) uncontrolled mining of amber; 4) negative impact on the ecology of the natural environment; 5) socio-economic consequences for the population of amber mining areas. “The predictive and search system for amber” (PSSA) allows solving these problems in a complex manner. The PSSA of Ukraine allows systematic research of “the amber-bearing formation” (AF) developed on its territory. PSSA uses scientific ideas about the origin of amber and the main natural factors of its formation, develops methods and a specific research algorithm. The main goal of PSSA is to identify “amber-bearing objects” (AO) in the geological body of the AF, which may contain high concentrations of amber, the so-called “traps”.

1. Introduction

In recent decades, the “amber” branch of the economy has been developing in Ukraine, which integrates the search for, mining and processing of amber. Ukrainian amber, thanks to its high quality, is recognized in the world and represents one of the most competitive types of domestic colored stones on the world market. The territory of Ukraine is promising for the discovery of placer deposits of amber, but their industrial development is currently carried out only within the boundaries of “the Pripyat amber-bearing basin” (PAB), which covers the regions of Volyn, Rivne, Zhytomyr, and Kyiv regions.

In a short time, the development of the “amber” industry of Ukraine caused a number of problems of a production, organizational, socio-economic and environmental nature. They significantly influence the socio-economic development of amber mining areas and at a certain stage were considered from the standpoint of national security of Ukraine [1, 2]. These problems can be presented as: 1) lack of a national program for the development of the "amber" industry; 2) its insufficient level compared to the real potential; 3) uncontrolled mining of amber; 4) negative impact on the ecology of the natural environment; 5) socio-economic consequences for the population of amber mining areas [3, 4]. A comprehensive solution to these problems is provided by "the predictive and search system of amber" (PSSA) [5–7].

2. Metods and materials

The methodology of general systems theory is used in the PSSA. The partial methods used are geological, geomorphological, paleogeographical, paleogeomorphological, laboratory data on amber, and statistical data on the socio-economic status of amber mining areas. The results presented in tables, graphically, on general and thematic maps of various scales, geological and geomorphological sections were further analyzed.

The article is based on the results of the authors' own research, obtained during the implementation of research work on amber in Ukraine, as well as international projects with the Republic of Belarus ("Development of a geological and genetic model of amber-bearing deposits of Ukraine and Belarus" with the financial support of the State Fund for Financial Development of Ukraine and Belarus) and the Republic of Poland ("Amber ways: deposits formation-mining. Scientific-methodical basis, rational use" and "Amber deposits and characteristics" funded by the EU). Stock materials (Geoinform) and geological expeditions of the Ukrainian Geological Company were also used.

3. Results

Lack of a national program for the development of the "amber" industry. The national program for the development of the amber industry in Ukraine is being formed, but its structure and connections of its components are clearly visible – forecasting, searches, development and exploitation of amber deposits, practical use of amber raw materials, regulatory and legal regulation, informational and educational and museum and educational activities. Currently, the amber industry in Ukraine is being developed by various state and private institutions, organizations, and individuals. The stage of spontaneous, chaotic development of the industry has passed and the primary experience of organized work has been acquired by it. To a large extent, this was facilitated by meetings, conferences, symposia on amber topics held in Ukraine and abroad, in which Ukrainian and foreign experts participated. Thanks to them, the content of the national program for the development of the amber industry in Ukraine was determined: active (anticipatory) conducting of forecasting and search for new amber deposits; the creation of state guarantees within the framework of international agreements between interested countries regarding the origin of trade batches of amber; development of quality certification schemes for Ukrainian raw amber and its adaptation to global schemes; establishment of legal and legislative norms of the optimal mode of extraction and sale of amber under the control of the state; in-depth comprehensive study of medicinal properties of amber, succinic acid, processing products and their introduction into medicine; launch of the "Polissya amber" brand and promotion to the international level. International conferences devoted to the topic of amber also made it possible to establish important contacts between scientists of different countries and in the future to carry out mutually beneficial joint interstate projects [8, 9]. This makes it possible to improve national programs for the development of the industry, in particular, to create the PSSA, which, over time, can be integrated into international ones. The PSSA will allow solving the main strategic task of the amber industry – the opening of new deposits of amber raw materials and the expansion of the market for amber products.

A necessary condition for the development of the amber industry in Ukraine is a clear and reliable legal framework. It is prescribed in the articles of the Constitution of Ukraine, Laws of Ukraine and Resolutions of the Cabinet of Ministers (CM) of Ukraine. According to them, the subsoil is an object of the right and property of the Ukrainian people (Constitution of Ukraine, Article 13). It is owned by the Ukrainian people and some of its representatives. On behalf of the Ukrainian people, the rights of the owner are exercised by state authorities and local self-government bodies within the limits set by the Constitution. On behalf of the Ukrainian people, the rights of the owner are exercised by state authorities and local self-government bodies within the limits set by the Constitution. The general procedure for the regulation of relations in the field of the study, extraction and sale of amber raw materials is carried out in accordance with the Codes of Ukraine – On Subsoil, Land, Forestry, Criminal, the Law of Ukraine "On State Regulation of Mining, Production and Use of Precious Metals and Precious Stones and Control of Operations with Them", by-laws adopted for their implementation. By this law, amber is classified as a precious stone of organogenic origin and a mineral of national importance [10–13].

Legal relations in the amber industry at the state level appeared in Ukraine only with the declaration of independence. In 1993, by Resolution (No. 111 dated February 18, 1993), the State Enterprise "Ukrburshtyn" was established for amber mining and processing. At the legislative level, changes were made to the Law of Ukraine "On entrepreneurship" (December 22, 1995), according to which amber mining is allowed only to state enterprises. After 10 years, thanks to the general development trends of our country, the Law of Ukraine (October 18, 2005) removed restrictions on amber mining only by state enterprises. Thus, the legislation in the amber industry determines that the subsoil and what is in it is the property of the Ukrainian people. Protection of the right to them is regulated by legislative acts of Ukraine.

In general, the legislative basis for the development of the amber industry in Ukraine has been created. Currently, only the issues of its normative and legal regulation are being proved. Complaints about the imperfection of the laws here are only partially justified. Laws must be obeyed by everyone – both those to whom it must be done "on duty" and ordinary representatives of society. Problems in the development of the industry began only after openly criminal elements became interested in amber.

At the same time, it should be noted that for the population of mining areas, "amber" is a profound issue. It is history, traditions, life – the opportunity to get an education, build a house, just live. They may not be at the scientific level, but they protect the ecology of their own home. In our opinion, the concept of "mentality" can be used here. Mentality is a combination of inherited (from past generations) and acquired (in current life) elements. The acquisition of the latter is served by the informational and educational and museum and educational directions of the development of the amber industry. Kindergarten, school, college, gymnasium, school, technical school, institute, university, olympics, newspapers, radio, television, Internet, conferences, exhibitions, expositions in salons and museums, specialized amber museums. As can be seen from the list, these areas can be developed systematically on the basis of existing organizational forms.

The insufficient level of development of the amber industry compared to its potential. In Ukraine, a significant database of lithological-facies, paleontological-stratigraphic, structural-tectonic, paleogeographical, geomorphological, paleogeomorphological studies has been accumulated. It gives grounds to predict that Ukraine has perhaps the largest reserves of raw amber in Europe. Currently, industrial amber mining is carried out within the northwestern part and the western slope of the Ukrainian Shield, where the main amber deposits of the PAB are located. However, the northern, northeastern, and southern slopes of the Ukrainian shield and the adjacent areas of the Black Sea and Dnipro-Donetsk depressions (and in the latter, adjacent to the southwestern spurs of the Voronezh anteclise) are considered promising for the discovery of amber raw material deposits. In these territories, in contrast to the PAB, the Paleogene lithological-stratigraphic horizons, which are promising for the discovery of new amber deposits, lie deep.

At the same time, the main resource of raw amber in the explored and currently developed deposits of the PAB is running out. The limitation of the raw material base is the main problem of the development of the amber industry in Ukraine. According to experts, its expansion in the PAB can be achieved by: 1) increasing amber production at known deposits 2) opening new deposits. The first way is limited by the natural and geographical conditions of the territory – all known deposits and manifestations of amber are located among valuable forest and land areas, under swamps; where productive horizons are located at a depth of 5-10 m. The amber in them is extremely dispersed. Outdated search data used by mining enterprises do not allow discovering new large deposits of amber. The second way – the discovery of new industrial deposits of amber is strategic and can determine the development of the amber industry in the coming years. The figure 1 shows fragments of some special maps of the PAB territory, which, in combination with other maps and materials, can be used to search for new types of amber deposits.

The figure 2 and figure 3 shows for the Dubivka area of the Volodymyrets group of deposits: maps: the paleorelief of the formation of promising amber-bearing horizons of the mezhyhirskya and obukhiv switas of the Paleogene (eocene-oligocene); the forecast of placer amber deposits.

Uncontrolled mining of amber. Uncontrolled amber mining causes the greatest damage to the state and the local population. Dangerous due to its predatory lack of control and the annual increase in the volume of shadow mining, it began to flourish in the country from the end of the 80s of the last century. This problem became especially relevant in the mid-1990s, when massive systematic illegal mining of amber covered a huge area of Polissya and prospectors began to use complex mining techniques.

The main reasons for the rapid increase in illegal amber mining are: the growth in demand for amber on the domestic and foreign markets; the possibility of mining with inexpensive, efficient equipment, due to the presence of productive layers close to the surface; the low level of employment of the local population in the districts of Rivne (Rokytniv, Zarichnen, Dubrovytskyi, Volodymyretskyi, Sarnenskyi), Zhytomyr (Olevskyi, Ovrutskyi), Volyn (Ratnivskyi, Manevytskyi, Lyubeshivskyi) regions, where the largest illegal amber mining currently takes place; low level of control of the authorities and law enforcement agencies over the activities of illegals; inadequate responsibility for the committed crime.

Currently, amber extraction by illegal miners is carried out by open (excavator-transport) and underground (motor pump) methods. The mined ore is enriched, washed on sieves. The empty rock is washed away, and the amber remains and is selected. The local population uses motorized pumps, with the help of which rocks are washed out from a depth of up to 10 m. This method belongs to complex underground.

Illegal amber miners mine manually and with the help of motor pumps wherever possible – in the forest, in meadows, in swamps and wetlands, on the banks of rivers and lakes, in exploited or abandoned granite quarries, in dumps, in terricones, within the boundaries of irrigation facilities, protected state facilities, under railway tracks, power line towers, in agricultural lands on all elements of the modern topography of the territory.

The level of qualification of illegal miners is also increasing. In the first years of illegal mining, there were mutilations among inexperienced executors, and frequent deaths of young people during the drilling of shafts in loose and waterlogged sands. Now, every year, an increasing number of qualified workers are involved in shadow production, and not only from among local residents, who unite in teams equipped with hand drills, motor pumps and other tunneling equipment.

Illegal extraction of minerals is classified as a crime, the consequences of which are manifested in the ecological, economic, and social spheres. According to estimates, the development of

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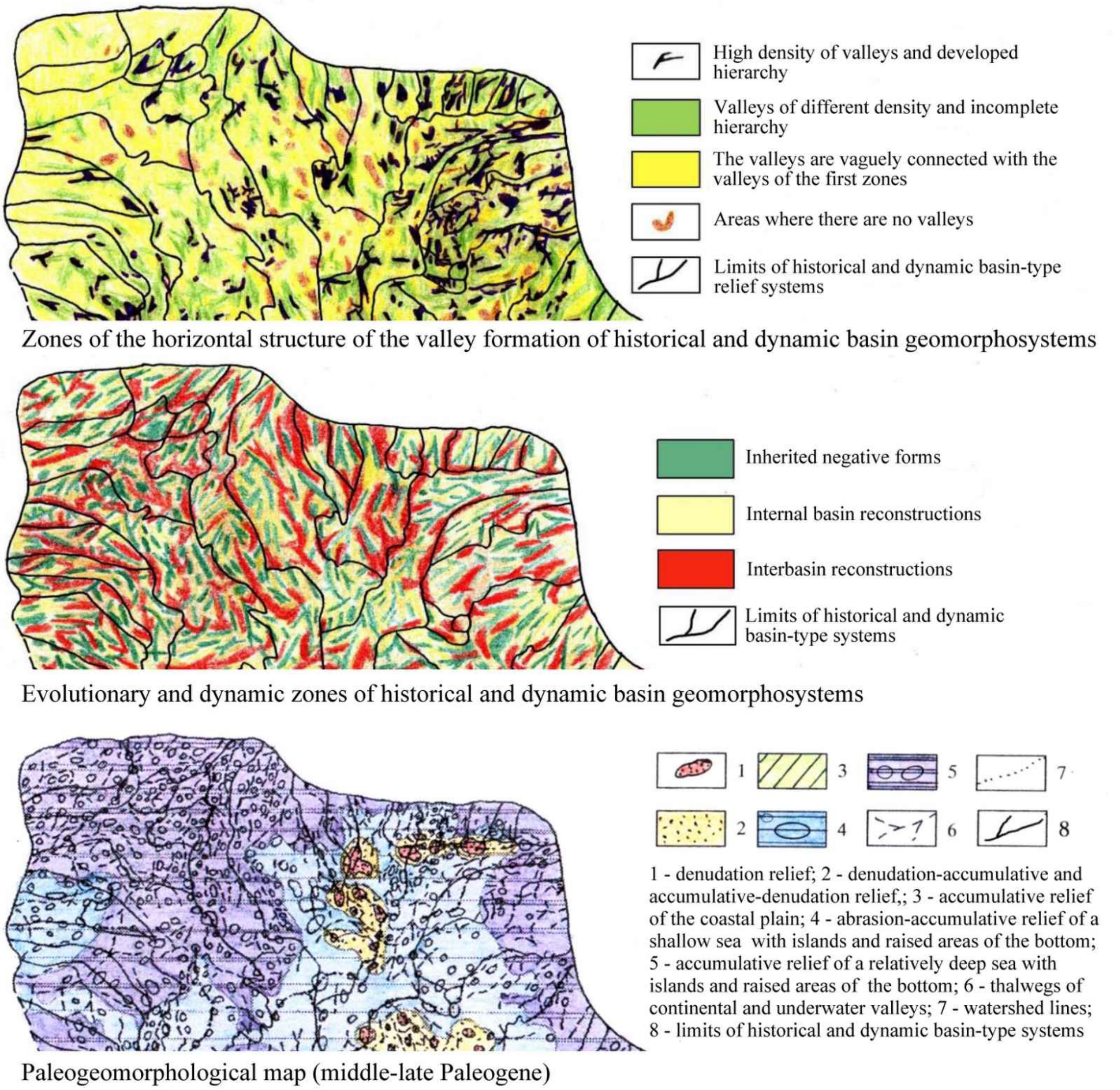

Figure 1. Special maps of the historically-dynamic geomorphosystem territory of the PAB.

amber costs the state UAH 8-10 million per day. According to various estimates, up to 30 tons are exported from the country annually.

To solve this problem, it is necessary to build relations with prospectors. In order to solve the problem of employment, individual prospectors are proposed to be united in prospector artels, for which the possibilities of obtaining permits for simplified subsoil use are opened. But here there is a question regarding the interpretation of the term “seeker”.

In most countries, a prospector is a person who extracts minerals without the use of heavy machinery, exclusively by hand. Therefore, for exploratory mining, it is advisable to transfer small-sized placers that can be developed in an artisanal way. In Polissya, the majority of such placers are located in the Zhytomyr region. It is proposed to introduce the category “local prospector – a citizen of Ukraine”, who is registered and lives in settlements located on amber

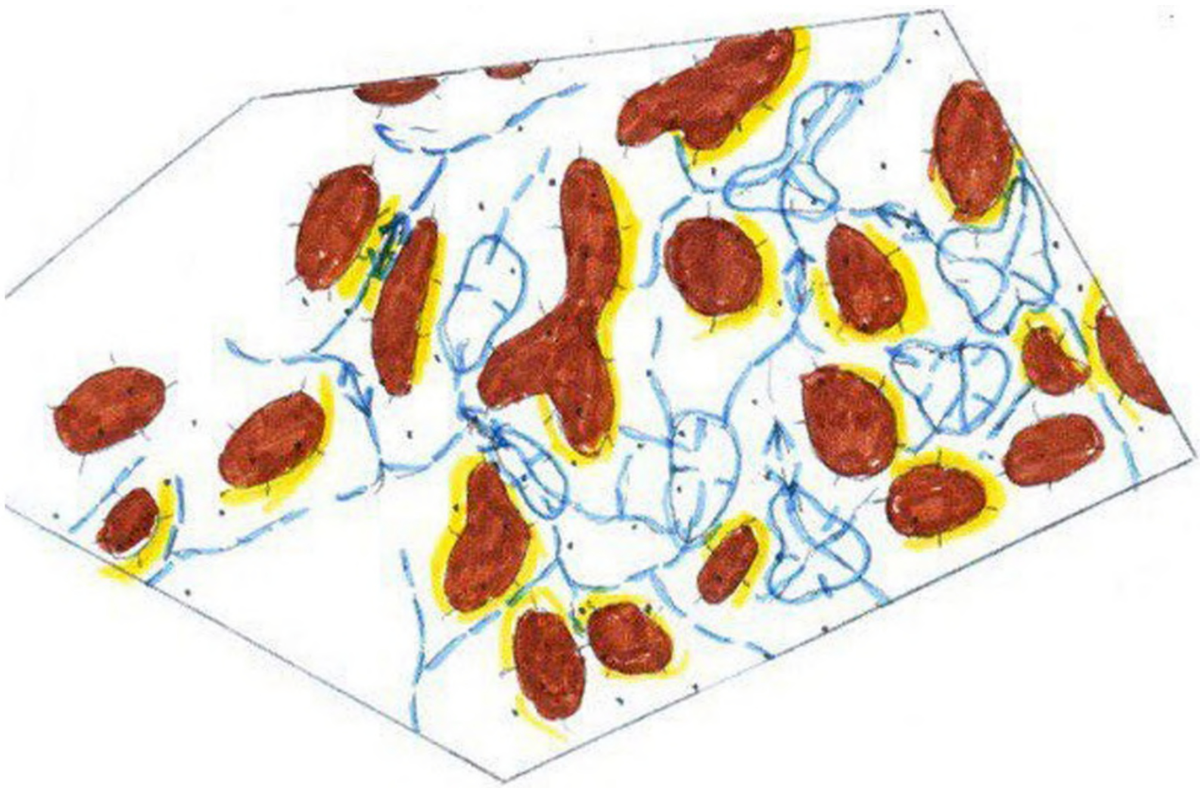

Figure 2. Paleorelief of the formation of promising amber-bearing horizons of the mezhyhirskya and obukhiv switas of the Paleogene (eocene-oligocene) (brown color – denudation relief of islands; yellow color – abrasive-accumulative relief of beaches; shallow sea bottom – thalwegs of underwater valleys, buried areas, directions of movement).

deposits, carries out its extraction and primary sale and compensates for the damage caused to nature as a result of such activities. It is proposed to introduce a special simplified taxation and reporting system for prospectors. In order to solve the issue of sales, it is proposed to create specialized exchanges in mining areas, where it is possible to legally purchase amber raw materials, as well as state points of purchase of mined stone.

The lack of a developed methodology for assessing damages caused by illegal amber mining leads to the state budget not receiving significant funds. The main criteria here are ecology and economy.

Violation of the legislation on subsoil entails responsibility: disciplinary, administrative, civil and criminal.

Negative impact on the ecology of the natural environment. According to the scale of impact on the natural environment of the territory of Polissya, the illegal activity of illegals is equated to the action of spontaneous natural processes. Currently, it is difficult to assess the extent of the damage caused by them. This problem is exacerbated by the fact that uncontrolled amber mining is imposed on the heavily damaged nature of this territory.

Illegal mining (pits-pits, ditches, hand-drilled wells, erosion of the soil with a motor pump) without proper backfilling of the trenches with waste rock disrupts the root system of trees, destroys the shrub and grass undergrowth, and leaves sand mounds and gaping pits filled to the top on the surface of the soil muddy water Problems arise with animals that fall into holes and cannot get out. In the forest, where the diggers have already visited, after a few years all the trees disappear, because the hydrological regime is disturbed by pits and pumps. Unauthorized

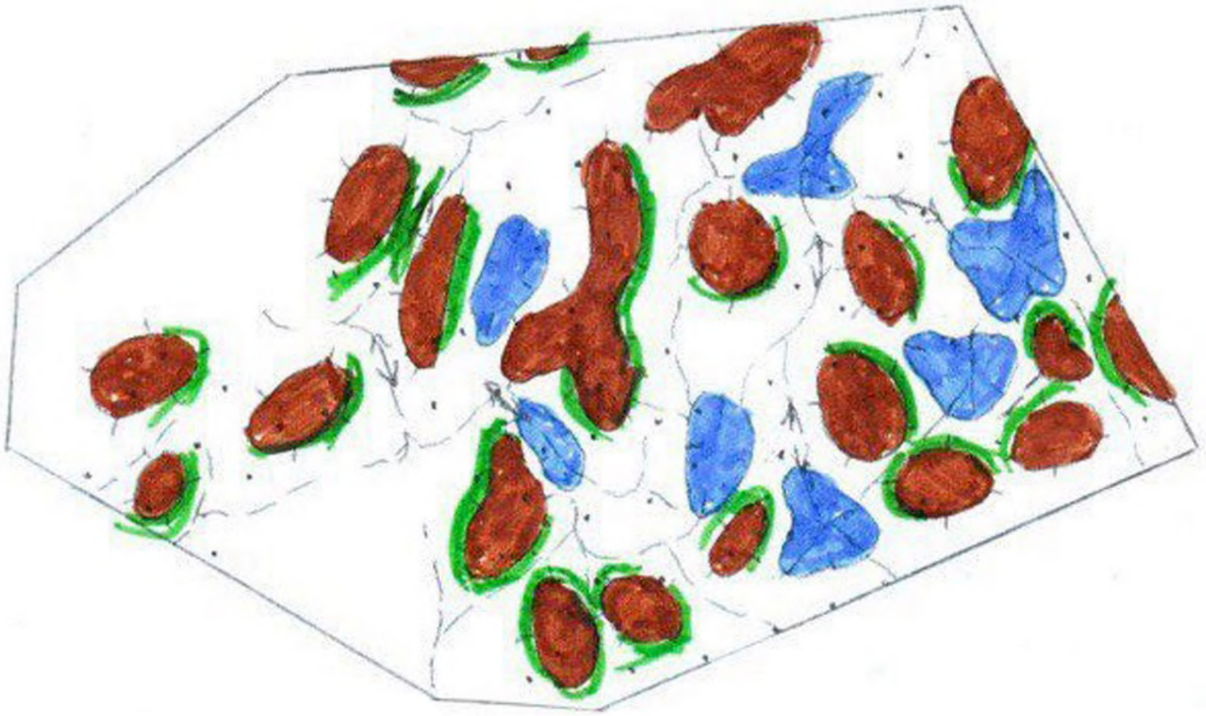

Figure 3. Forecast of placer amber deposits Dubivka area (brown color – low islands – places of wear and tear; green color – bench, beaches – accumulation of large fractions of amber; blue color – buried trap areas – accumulation of large fractions of amber).

mining, which is carried out by hydromechanical methods, devalues productive horizons and deposits lose their industrial value (figure 4).

Very often, amber is mined within the protected natural areas – nature reserves, nature reserves, etc. Violation of the territorial regime makes it impossible for many species of protected animals to exist here.

Illegal mining of amber leads to the destruction of surface (4-5 m) productive horizons. Illegal prospectors choose high-quality and most valuable amber, and the "small stuff" that can be successfully used in many industries remains in the dumps.

Illegal mining of amber in recent years has created another environmental problem – the burning of charcoal. Deliberate arsons are carried out, fallen trees are burned.

Thus, illegal mining of amber affects all components of the natural complex: soils – by removing the fertile layer, disrupting the structure of the soil cover, clogging the land plot, which causes loss of humus, macro- and microelements, destruction of the upper fertile layer, increased wind and water erosion; vegetation – violation of the integrity of the grass cover, illegal destruction of trees, which leads to the violation of the integrity of the grass cover, drying and destruction of trees; animals – by violation of the usual mode of living of animals, the creation of an unusual man-made terrain for them, which leads to the migration of animals to other places, their mutilation, death; water – arbitrary, uncontrolled use of surface and underground water, which leads to a violation of the hydrological regime of the territory, a decrease in the level of groundwater; air – as a result of the burning of fuel and lubricants, the burning of charcoal, the atmosphere is polluted with CO_2, CO, SO_2, NO_2, and hydrocarbons; subsoil – violation of the geological structure of the territory, loss of subsoil, which leads to deformations of the earth's surface, damage to mineral deposits, restriction or complete removal of them from exploitation,

Figure 4. Consequences of illegal amber mining in Zhytomyr region.

impoverishment of subsoil.

Illegal amber mining exacerbated the problem of reclamation of disturbed lands, which is important for the organization of rational amber mining and prevention of the destruction of natural landscapes. This problem should be solved by specialized organizations that have mastered the methodology and have experience in similar work. Reclamation of disturbed lands takes place during 3 stages – preparatory, hydrotechnical, biological. In the preparatory stage, a survey and typification of disturbed lands is carried out and the type of reclamation is chosen. In the hydrotechnical stage, land vacated after mining operations is prepared for their further use. At this stage, the following is carried out: selective removal, storage and preservation of overburden suitable for biological reclamation, including the fertile layer; selective formation of overburden dumps; if necessary, planning and covering the planned surface with a layer of soil; backfilling and planning of deformed surfaces; creation of access roads; drainage and anti-erosion measures. The biological stage of reclamation consists in restoring the fertility of disturbed lands, restoring flora and fauna by agrotechnical and phytoremedial means.

Socio-economic consequences in amber mining areas. Illegal mining of amber within the territory has revealed many shortcomings of modern social life, these are: lack of an effective system of combating illegal mining, use and circulation of amber in Ukraine; the invalidity of some laws regarding the protection of subsoil and the regulatory and legal support of labor activities on the extraction, production and use of amber; low level of environmental education of Ukrainian citizens, primarily young people; social roots of criminal activity (unemployment, etc.).

The results of the work were discussed at scientific and practical conferences in Ukraine and abroad (Poland – Ambermarket, Amberif), scientific seminars at the Polish and Ukrainian

Academies of Sciences.

4. Conclusions

All these problems have a complex nature and cover various aspects of the socio-economic, cultural and political life of the country and can be solved exclusively at the state level. This requires the adoption of a number of state laws and, first of all, the law on preserving the country's national wealth – amber and protecting it from looting. Without the adoption of these laws, the scale of theft will increase, which will lead to the disappearance of the upper productive horizon and the transformation of Polissya into a desert.

The PSSA should solve the mentioned problems of the amber mining areas.

The PSSA of Ukraine allows systematic study and use of AF developed on its territory. The PSSA takes into account scientific ideas about the origin of amber and the main natural factors of its formation, develops methods and a certain research algorithm.

The AF represents a special type of sedimentary geological formations, since their central, formation-forming element (amber) at the beginning of its formation came from the biosphere, and not from the lithosphere (as in most geological formations).

The AF is formed by the processes of tectogenesis, morphogenesis, lithogenesis, oreogenesis of amber, which interact systematically. As a result, tectonic (neotectonic) structures, landforms, deposits, amber deposits are formed. The AF of Ukraine is constantly being studied. In general, its spatio-temporal parameters, structure, trends of transformations of the geological "body" of the AF are understood. Within the boundaries of the PAB, the geological body of the AF is exposed on the surface almost everywhere, intersects with modern (and ancient) "geomorphological formations", which are parts of the historical-dynamic geomorphosystem.

The main goal of the PSSA is to forecast and search for the AOs located in the geological body of the AF. AOs include natural formations or their parts that contain or may contain concentrations of amber. The accumulated experience of amber exploration allows to distinguish stratigraphic, lithological-stratigraphic, lithological, structural-tectonic, paleogeomorphological, geomorphological types of the AOs.

The specific stratigraphic horizons of the Paleogene system (charkiv, mezhihirsky, obukhiv layers) in which primary amber-succinite placers are found belong to the stratigraphic AOs on the territory of Ukraine. This also includes the stratigraphic horizon of the buchac svita of the middle Eocene, the amber-like resins from which, according to many researchers, were the starting point for the formation of the AF of Western and Eastern Europe. AOs of the lithological-stratigraphic type are revealed in the process of detailed study of promising Paleogene horizons. Lithological AOs are "lithological bodies-collectors" that are found in Neogene and Quaternary stratigraphic horizons, in particular cross-cutting "lithological bodies" that cover several stratigraphic horizons. Identification of the structural-tectonic type of AOs requires the use of structural-tectonic models of the tectonosphere for the time of formation of the AF. It will show the tectonic (neotectonic) structures that are dynamically active in the Neogene-Quaternary (neotectonic) time – newly formed or inherited from the morphostructures that formed during the Mesozoic. These structures could influence the processes of lithogenesis and morphogenesis from the time of the accumulation of amber-like resins (middle Eocene), the formation of primary amber-succinite placers (late Eocene-Oligocene), the destruction of primary deposits, redeposition of their derivatives, the emergence of new placer deposits in Neogene and Quaternary horizons. In order to identify paleogeomorphological and geomorphological AOs, it is necessary to have a modern understanding of the "relief" as a "historical-dynamic geomorphosystem" and take into account the peculiarities of its functioning. This approach makes it possible to identify potentially possible relief forms of various stages of the development of the AF on a systematic basis.

The use, as a basic, geomorphosystem factor, allows to search for AOs on a scientific basis, which is important for geoecology and protection of the natural environment in amber mining areas.

It is important to note that the main goal of organized and illegal amber miners today is the search for AOs of stratigraphic and lithological-stratigraphic types. This is influenced by the underground occurrence of AF, which allows the use of available and cheap technologies for the development of amber and does not require the use of relatively expensive scientific developments.

The PSSA of Ukraine contributes to the strategic development of the amber industry in Ukraine, which consists in a comprehensive approach to solving the scientific and practical tasks of finding and developing amber deposits, socio-economic and environmental problems. The concept of the AF creates scientific and methodical conditions for this.

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References

[1] 2020 *National security of Ukraine in the challenges of recent history* (Kyiv, Ukraine: Express-announcement) ISBN 978-617-7389-16-2 URL https://doi.org/10.5281/zenodo.3577932
[2] Rudko H Y 2019 *Natural problems of Ukraine's national security in the challenges of recent history* (Kyiv, Ukraine: Bukrek) ISBN 978-617-7770-24-3
[3] Komliev 2022 *Some problems of development of the amber industry of Ukraine* (Kyiv, Ukraine: Taras Shevchenko National University of Kyiv) URL https://drive.google.com/file/d/1L-gqRcZXiKcX03z-UMMJt9vFUTTUlEjM/view
[4] Komliev O O, Bortnik S Y, Remezova E O, Zhylkin S V, Pogorilchuk N M and Filonenko Y M 2020 "Paleogeomorphological atlas" as a way to accumulate generalized and obtain new information "historical-dynamic morphosystem of the Earth" *Geoinformatics: Theoretical and Applied Aspects 2020* vol 2020 (European Association of Geoscientists & Engineers) pp 1–5 ISSN 2214-4609 URL https://doi.org/10.3997/2214-4609.2020geo003
[5] Matsui V 2016 *Evolution of resin-producing vegetation and formation of deposits of fossil resins* (Kyiv, Ukraine: Naukova dumka)
[6] Savkevich S S 1970 *Amber* (Nedra)
[7] Trofimov V S 1965 Amber placers and their origin (Nauka) pp 77–97
[8] 2008 *Amber of Ukraine. Materials of the First International science and practice conf. "Ukrainian amber world"* (Kyiv, Ukraine: Institute of Geological Sciences, NAS of Ukraine)
[9] Komlev O O, Remezova O O and Filonenko Y M 2008 Geomorphological-paleogeomorphological basis of exploration for amber (Kyiv, Ukraine) pp 95–100
[10] Verkhovna Rada of Ukraine 1997 On state regulation of mining, production and use of precious metals and precious stones and control over transactions with them URL https://zakon.rada.gov.ua/go/637/97-%D0%B2%D1%80
[11] Cabinet of Ministers of Ukraine 2011 On approval of the procedure for granting special permits for subsoil use URL https://zakon.rada.gov.ua/go/615-2011-%D0%BF
[12] Cabinet of Ministers of Ukraine 2011 On approval of the procedure for holding auctions for the sale of special permits for the use of subsoil URL https://zakon.rada.gov.ua/laws/show/594-2011-%D0%BF#Text
[13] Verkhovna Rada of Ukraine 1994 The Code of Ukraine on Bowels URL https://zakon.rada.gov.ua/laws/show/132/94-%D0%B2%D1%80?lang=en#Text

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Mining tourism as a guarantee of sustainable development of industrial regions (on the example of Kryvyi Rih region)

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Mining tourism as a guarantee of sustainable development of industrial regions (on the example of Kryvyi Rih region)

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Abstract. Sustainable tourism is fundamentally about preserving and enhancing natural, historical, or cultural heritage, as well as promoting activities related to local identity and history. For mining regions, one of the ways to diversify their economies on a sustainable basis is to develop the tourism sector. The development of niche forms of tourism, which are fully focused on the resources of the industrial area, helps to supplement and diversify the tourist offer in these regions, including industrial tourism and one of its areas - mining tourism. The objective of the study is to reveal the importance of sustainable development for an old industrial region, using Kryvyi Rih as an example, by intensifying tourism activities that would maximize the social, economic, cultural, and environmental benefits of tourism. The research is based on the dialectical method of cognition and a systematic approach. The research was carried out on the basis of parallel use of theoretical (comparative analysis, abstraction, specification and generalization) and empirical methods (expeditionary methods, observations, the method of field visual inspections, content analysis, etc.) As a result of the study, approaches to the concept of "mining tourism" were structured, and the key objects of interest of consumers of this tourist destination were identified. Global trends in the transformation of industrial areas for the needs of mining tourism were analyzed. The information on mining facilities in Kryvyi Rih is systematized and their suitability for the tourism sector is diagnosed. Based on the diagnostics, the use of various mining facilities in thematic tour programs is proposed, which is confirmed by the results of practical tourism activities.

1. Introduction

For a long time there have been discussions in various scientific sources about the interpretation of the term "sustainable development" and its understanding in order to direct the further harmonious development of the triune global system "nature-economy-society". In general, the understanding that further development of society on the planet will be limited by the irrational use of natural conditions and resources led to the emergence of the paradigm of sustainable development in the 1970s. The UN is the leading organization aimed at ensuring of the implementation of the paradigm itself and the achievement of its goals at the global level. The regional and local levels are implemented at the level of individual regions and countries of the world. Since "sustainable development" should ensure the rational use of natural conditions and resources, the attention is usually paid to its ecological essence.

Therefore, in the vast majority of sources sustainable development is defined as the development that enables to meet the needs of current generations and leaves the opportunity for future generations to meet their needs. This is the balanced development of the country and regions, where economic growth, material production and consumption, as well as other types of social activities take place within the limits determined by the ability of ecosystems to recover, absorb pollution and support the livelihoods of current and future generations. The key tasks of sustainable development are determined by the following: restoration and further preservation of natural ecosystems and their ability to self-reproduce in the required volume on the required area; ensuring anticipatory solution of the problem at the same time: economic, social, demographic and spiritual development.

In order to ensure sustainable development and control the indicators of the implementation of the paradigm for a specific time period, the Law on the Strategy of Sustainable Development until 2030 was adopted in Ukraine. The concept is based on the 17 global Sustainable Development Goals adopted at the UN Sustainable Development Summit. In particular, the following important provisions are defined in the strategy: as a result of the dominance of resource- and energy-intensive industries and technologies over many years, the raw material orientation of exports and the excessive concentration of production in industrial regions, such a structure of development management was formed, which is generally inefficient and environmentally dangerous; the level of economic development and welfare of the population does not correspond to the natural, scientific and technical, agrarian and industrial potential of Ukraine and the qualification and educational level of the population, socio-historical and cultural traditions of Ukrainian people; Ukraine has international obligations regarding sustainable development, defined by UN strategic documents; the basis for the implementation of innovative transformations in Ukraine in the direction of sustainable development is the Association Agreement between Ukraine and the European Union, etc. [1].

Tourism is a part of the economic system that has been developing most actively in recent years; even the COVID-19 pandemic, which had a negative impact on international tourism in general, on the other hand stimulated the development of domestic tourism within countries (especially in Ukraine). In this sense, tourism, like any other branch of the economy, performs a dual role: on one hand, it provides income and stimulates the development of individual territories, on the other hand, it brings a significant imbalance to the development of ecosystems (due to seasonal population growth, in particular, the volume of the use of local resources, more household waste is produced, pollution of all components of ecosystems increases, as production volumes of all industries increase).

Thus, it is quite fair to apply the concept of sustainable development to tourism as well. The term “sustainable tourism” is widely known. UNWTO defined sustainable tourism as “tourism that takes full account of its current and future economic, social and environmental impacts, meeting the needs of visitors, industry, the environment and host communities” [2].

According to UNWTO, several conditions must be met for sustainable tourism: rational use of environmental resources and conditions and preservation of natural heritage and biodiversity; tolerant and careful attitude towards authentic host communities; provision of long-term economic development programs taking into account socio-economic benefits for all stakeholders (both tourists and local residents, tourism organizers). UNWTO and UNEP have specified these provisions and defined 12 goals for sustainable tourism.

A rational approach to the use of natural resources is possible when we understand the finitude of these resources (bright examples of post-industrial cities and towns are ghost towns scattered around the world, where life has recently been raging). Over time, the mining areas remain devoid of economic prospects for development and, in fact, are ecologically unpromising and unattractive for development. However, the development of mining tourism using the existing industry (dumps, quarries, mines, reservoirs) and objects of industrial heritage (used quarries and reservoirs in them, abandoned mines and backfills, old mines and tunnels) is an important economic, environmental incentive for the prospective development of mining areas, allows to diversify the economy. In fact, tourism within mining areas is an important tool that, in addition to reducing environmental hazards, can help to preserve heritage and bring the economic revitalization to surrounding areas.

2. Literature review

Mining regions are territories with different spatial coverage, which were formed as a result of the extraction of minerals from the bowels of the earth, thus they are territorially tied to deposits of mineral raw materials or entire basins. Mining regions are formed as a result of close interaction of the processes of human activity with the use of technical means and natural processes inherent in a specific natural zone. As a result of such a complex genesis, mining regions are characterized by a significant imbalance of development; they are characterized by not just the manifestation of natural processes and phenomena, but new ones, which are defined in the literature as accompanying, natural-anthropogenic, anthropogenic, natural-technogenic, post-technogenic processes. According to H. Denysyk and H. Zadorozhnya: "The mining landscape itself is under the influence of exogenous and to some extent endogenous natural processes (modern and neotectonic movements of the earth's crust). The totality of the action of human industrial activity and natural processes generate processes that are layered on the created mining-industrial complex" [3].

A number of works are devoted to the study of the problem of sustainable tourism in industrial and mining regions. Leonard [4] raise the acute issue of creating an economically profitable industrial facility in one of the tourist attractive regions of South Africa (opening of a mining enterprise) or an alternative option of creating a tourist facility (a facility world heritage Mapungubwe, Limpopo), focusing on greater perspective and ensuring sustainable development of the second [4, 5].

The work of Jonsen-Verbeke [6] is of interest and dedicated to the creation of sustainable tourism enterprises based on former industrial and mining areas. It is in this aspect that this study points to the relevance of the scientific search of the authors of this article, since the authors consider the development of mining tourism in the territory of Kryvyi Rih as a promising economic stable way for further development of an industrial city, taking into account all the requirements of sustainable tourism. Herdiansyah et al analyses possible options for the further use of post-industrial areas, one of which is ecological tourism, since it is most aimed at achieving the goals of sustainable development of heavily changed, damaged areas of the ecosystems of mining areas [7].

Ilkovičová and Ilkovič consider the possibilities of combining industrial tourism with educational and ecological ways of creating mining educational trails, entire geoparks in the territories of mineral extraction (for example, in Slovakia, Spiš, Gemer, a well-known area around Banská Štiavnica) [8]. According to the authors, this approach will make it possible to keep the economic development of post-industrial areas stable and restore their ecological potential (with the use of reclamation and revitalization means).

First of all, the studies, focused on the need to preserve industrial, including mining heritage, began to appear in the scientific literature. The issue of including mustard objects in tourist activities began to be raised much later. Accordingly, it can be noted that a number of scientific approaches have been formed regarding the interpretation of the concept of mining tourism and its combination with certain types of tourism.

There is a cohort of scientists who interpret mining tourism exclusively through the lens of heritage. In particular, Różycki and Dryglas note that mining and tourism activity are growing side by side in different regions around the world [9]. Some of the mines are closed after the end of operation. This creates an opportunity for the development of mining tourism [10]. In our opinion, this interpretation somewhat narrows the essence of mining tourism exclusively to its consideration through the prism of heritage. Quite a large number of scientists from different countries of the world use the concept of mining heritage tourism directly in their research, but the study of Cole [11] is considered one of the pioneers, in particular, he considered the transformation of reserve areas of coal mines into objects of industrial heritage in accordance with the goals of sustainable development. We will undertake research into the sustainability of UK mining heritage sites as viable tourism businesses, using the results of the UK Mining Heritage Survey conducted in 2002 [11].

Edwards and Llurdés i Coit examine the importance and perception of mines and quarries in the article "Mines and quarries: Industrial heritage tourism" as foci for industrial heritage tourism and its expansion during the last decades [12].

Jelen considers mining tourism as one of the forms of conservation, interpretation of mining heritage and its transmission to the next generation. At the same time, he emphasizes that "It is also important to find a balance between all the functions of heritage, and not to focus on only some of them for the needs of tourism. Mining heritage may meet the needs of tourism, but it should not be subordinated to these needs and created solely for the purpose of generating income" [13].

Mining tourism can be seen as an important process that helps both to interpret the mining heritage and to serve as a further source of employment and business activity after mining has ended. It is valued as a driving force that may stimulate the economic potential of mining heritage and contribute to its preservation in a form that is able to generate income [14].

In many studies, mining tourism is considered as a component of geotourism. In particular, numerous studies assess the potential of mining sites or regions for the development of geotourism [5, 7, 12, 15–17].

Slovak scientists led by Rybár carried out a significant fundamental work on revealing the structure and features of this tourist destination [18, 19]. Thus, Rybár and Štrba [19] define mining tourism as a form of tourism for both specialists and general public (laics) allowing visitors, via on-site visits of mines, museums, and cultural-historical monuments related to mining activity and life of miners, and ex-site visits of museums with mining expositions, to feel a bond with one of the oldest human activities – raw material extraction, situated and developed mostly in underground over centuries and connecting the visitor with his/her ancestors [20]. In general, analysing the relationship between mining tourism, industrial tourism and geotourism, these scientists come to the conclusion that "mining tourism should be recognized as an equivalent form of tourism, compared to geotourism and industrial tourism".

There is a group of scientists who see mining tourism in the structure of industrial tourism. In particular, Schejbal considers mining tourism a type of industrial tourism that aims to trace the development of mining disciplines and their practical impact on the history of human society [21]. At the same time, the scientist notes that the theoretical basis of mining tourism is the most problematic. The reason is that it is a complex transdisciplinary branch of science that uses earth sciences, related technical disciplines and socio-economic disciplines. Caamaño-Franco and M. Suárez though studying the planning of industrial mining heritage as a tourist attraction, but also consider it in the context of industrial tourism [22].

In recent years, the studies have increasingly used the term "post-mining tourism" [5, 20, 23], which provides for the organization of tourist activities in territories where the active process of mineral extraction has been terminated. Indeed, reimagining post-mining spaces and turning them into tourist spaces has proven to be a successful strategy for mining regions.

Numerous studies devoted to the formation of mining tourism in various geographical locations testify to the importance and relevance of this direction for mining regions. In particular, such locations are Kiruna, Pajala and Jokkmokk in Sweden [24], Las Médulas [22] and Andalusia (Linares, Alquife, Seron and Villanueva del Río y Minas) in Spain [25], Northern

Australia [26], Lota y Coronel territory in Chile [27], Ouro Preto, Chapada Diamantina, Ametista do Sul, Currais Novos and Itu in Brasil [28], Upper Silesia in Poland and Czech-Moravian country in the Czech Republic [6], Nor-Pas-de Calais in northern France [29] and many others. Similar examples of the creation of projects or already implemented ideas of sustainable tourism within mining territories are abundant in various regions of the world.

3. Methodology

The research is based on the dialectical method of cognition and a systematic approach. The research was carried out on the basis of parallel use of theoretical and empirical methods. Theoretical research was carried out using the methods of comparative analysis, abstraction, specification and generalization. The method of content analysis was used in the study of archival documents on the development of mining in Kryvyi Rih basin, various project documentation of operating industrial facilities, international documents on preservation of industrial heritage, and successful foreign examples of successful establishment of mining tourism.

The empirical component of the study included the following stages:

1. **Analysis of the terrain.** In the course of numerous expeditions to the area during the years 2004–2021, photo-fixation was carried out and the remains of industrial heritage objects were studied, which gave grounds for asserting the presence of tourist potential of these objects.
2. **Preparation of recommendations** regarding the preservation of industrial, including mining, heritage and its use in tourism. In the current period, since 2013, the city has adopted a program for development of industrial tourism, in which implementation the authors of the study were actively involved.
3. **Approbation.** Since 2013, the authors of the study have prepared a number of highly specialized excursions on mining topics, as well as complex tours to the city on industrial topics in general. This made it possible to visually assess the impressions of tourists from each visited object, as well as to analyse the objects not only from the standpoint of scientific, in particular, historical and geological value, but also in terms of their tourist attractiveness and safety for tourist activities.
4. **Selection of the most attractive mining objects for tourism.** The development of comprehensive tours of the mining theme in the city of Kryvyi Rih involved the selection of key objects and their prioritization. For this purpose, criteria for the selection of objects were formed, on which basis the most attractive objects for visiting, able to satisfy the aesthetic and cognitive needs of potential tourists, were chosen. For each of the types of mining objects (quarries, dumps, sinkholes, etc.), diagnostics was applied, which included an analysis of the positive and negative aspects for tourist activity. The application of these diagnostics enabled to select the most suitable tour programs for a certain thematic from the entire cohort of available objects.
5. **Offers for mining tourism.** The significance of mining tourism as an important direction of industrial tourism, which development has been supported in the city since 2013 at the municipal level, is substantiated; a mining-themed route has been developed; recommendations have been made on adaptation of mining facilities for visiting and the activation of tourist activities in their environment.

The use of this methodological apparatus is aimed at rethinking the tourist potential of the region in view of the significance of not only the objects that can arouse the interest of tourists, but also the importance of the mining activity of the industrial region itself.

4. Securing informed consent for image utilization

The images featuring individuals in this research were captured by the authors of this study, primarily Volodymyr Kazakov and Viktoriia Patsiuk. Both authors are certified tour guides affiliated with the All-Ukrainian Association of Guides (Civic Union "Ukrainian Tourist Guides Association"), an organization that holds partnerships with esteemed entities such as the World Federation of Tourist Guide Associations and the European Federation of Tourist Guide Associations.

The authors strictly adhere to global standards for personal data protection and respect for individual privacy. Before initiating any tour, explicit consent is obtained from participants for their photographs to be taken. Participants are informed that these images may be utilized for scientific, educational, or promotional purposes. Individuals who prefer not to be photographed are respectfully excluded from the images.

In line with the journal's policy on publishing identifiable individual data (`https://publishingsupport.iopscience.iop.org/ethical-policy-journals/`), we have meticulously followed a robust procedure to secure informed consent from all individuals whose images are featured in this article. This section provides a detailed account of our methodology to ensure full compliance with ethical guidelines and the journal's stipulations regarding image use.

1. *Identification of individuals*: Figures 6 and 8 are identified as containing identifiable human subjects. These individuals represent a diverse group, including research study participants and other relevant persons whose images are included.
2. *Contact and consent*: We proactively reached out to each of the 12 identifiable individuals included in our manuscript. Our communication encompassed a thorough explanation of why their images were being included in this article, addressing any queries or concerns they might have had about the publication.
3. *Documentation*: To ensure transparency and compliance, we meticulously documented all instances of consent obtained. For each individual, we maintained a record of the consent form, which included their explicit agreement for their images to be used in this article.
4. *Awareness of intended publication*: We confirmed with each identifiable individual that they were fully cognizant of the intended publication of their images in this manuscript. We ensured that they understood the context in which their images would be used and the potential for a broad readership.
5. *Ethical considerations*: Throughout this process, we remained committed to adhering to ethical guidelines and regulations governing the use of images in research publications. Our primary objective was to respect the privacy and dignity of all individuals featured in our article.

Additionally, we would like to express our gratitude to Dmytro Antonov for his consent to publish a photograph taken by him.

5. Results

Usually, mining, mining-industrial, post-mining-industrial regions are perceived as territories with an extremely tense ecological situation, severely disturbed landscapes (badlands), as unattractive for life, for development of various types of economic activity and tourism as well. However, using the concept and goals of sustainable development, it is possible to change such a sharply negative perception, due to the active involvement of such regions in various types of industrial tourism. For example, if several new forms of anthropogenic relief were created within a certain natural landscape as a result of mining (for example, a quarry, dump, sump), this leads to the appearance of new types of landscapes, and usually contributes to an increase in the contrast of the environment, and in future, the growth of its attractiveness, the possibility of many options for further development.

Mining regions that combine operating industrial enterprises, objects of industrial heritage, and post-industrial objects within their territory essentially have a whole range of options for prospective sustainable development. One of these options is mining tourism, with means of which it is possible to attract numerous tourists to mining areas.

Having analysed the existing approaches to the interpretation of the concept of mining tourism, we believe this tourist direction does not belong to the structure of geotourism, since in our understanding geotourism is aimed at studying and visiting mainly natural objects. Although, indeed, quite often geotourism and mining tourism have a common object to visit (exposure of mineral deposits, rocks exposed in mines, etc.). At the same time, when the concept of mining or industrial heritage tourism is used, the attention is focused only on heritage objects. A similar situation is with postmining tourism, where the emphasis makes on visiting transformed objects, so these subspecies absolutely exclude the production component. However, the objects of active industry are working mines, functioning mining and beneficiation plants definitely are and can be objects of mining tourism. Therefore, we defend the opinion that mining tourism is an autonomous direction that is a part of the structure of industrial tourism, which combines heritage objects, active industry and regenerated production objects.

As Rybár and Hronček claim, a mining tourist is particularly interested in [18]:

- mining traditions,
- unique machinery,
- modern mining technology,
- illegal visits of underground mines (adrenaline, adventure, illegal collection (robbery)),
- special events in the underground (weddings, concerts, masses, celebrations),
- sports activities (adrenaline sports: rock climbing, motocross, mountain biking, underground collective sports: football, table tennis),
- recreation and wellness (recultivated mining works after surface mining: swimming, sunbathing, walking, in modified spaces of underground mines: health stay rehabilitation (resting, sleeping) in the unique conditions of some types of rocks, jogging, Nordic walking,
- geology, mineralogy, paleontology, collecting, ecology, and biology, unique fauna moreover, flora occurring during and after the mining activity as well as in the recultivated area,
- free time activities utilizing vast spaces (mostly connected to surface mining – tank driving (!), paintball, cross golf),
- other.

Ukraine has a significant potential for development of mining tourism, where work on extraction of various minerals was and is being actively conducted. Kryvyi Rih is a city with the largest range of mining facilities and landscapes. This is due to [30]:

- 8 main and 37 auxiliary iron ore mines here;
- 9 operating quarries, 8 of which are iron ore and 1 is a granite quarry;
- 39 completed quarries;
- 85 dumps;
- 26 failure zones and displacement zones in mine fields of underground mines;
- 15 sludge storage facilities of mines and mining and beneficiation plants;

- 34 speleological objects: 12 open shafts of mines (one lignite and the rest iron ore), 3 shafts (the old mine "Chervonyi Hirnyk", the old mine of Kolachevskyi, the collapsed mine "K-D-1"), 11 tunnels (Kochubeyivskyi, Rakhmanivskyi, Pokrovskyi, etc.), 2 underground workings (at the old Kochubeyivskyi mine), 1 shaft (Northern ventilation mine), 2 downhole shafts of Kozatska mine, 3 gesenks of rising workings (in the ceiling of the shaft of the old Northern ventilation mine and on the sides of the bottom shaft of the mine "K-D-1");

The presence of the listed objects is a powerful resource base for the development of industrial tourism in general and mining tourism in particular. In 2013, the city adopted the Industrial Tourism Development Program for 2013–2015 [31], which was subsequently extended until 2020 and then until 2024 inclusive [32]. After that, active work started to transform an exclusively industrial city into a tourist destination.

However, expeditionary studies of the mining heritage and landscapes of the city took place long before the adoption of the program. Back in 2004, local history work on the study of these objects was initiated by the geographer Volodymyr L. Kazakov, who was joined by his colleagues and students. This made it possible to create a register of mining objects in Kryvyi Rih. With this, the work on development of tourist activities at mining facilities started. One of the directions of this work was a detailed study of mining sites, analysis of their tourist potential and creation of excursion routes. The preparation of these routes and their implementation for both citizens and city guests made it possible to determine the list of the most attractive objects in a practical way that are able to stimulate tourists to come to Kryvyi Rih.

The following were the criteria for selecting objects for their inclusion in the tour programs:

- uniqueness and feature of the object;
- significant morphometric parameters;
- the historical significance of both the phenomenon of industrial heritage and from the point of view of the introduction of innovative technologies at these objects in a certain period of time;
- the possibility of access to the object (convenience of entrances and approaches, the possibility of entering without various agreements with enterprises);
- the object illustrates the processes of natural renaturalization and reclamation;
- the object is a part of the cultural landscape of this region and has an aesthetic appeal.

The existing criteria made it possible to determine the key ones for tourists to visit from the entire list of objects. As experience and communication with tourists show, working quarries and mines arouse the greatest interest among visitors. And if the quarries were visited on a permanent basis, and the open pit of Southern Mining-and-Processing Plant was generally considered the most iconic industrial monument of the city, which is included in the ERIH network [33], then the visits to the mines took place very fragmentarily. Although the Kryvyi Rih mines are the deepest mines in Europe ("Yuvileyna", –1720; "Ternivska", –1620, "Kozatska", –1615), and their headframes are figuratively called "Kryvyi Rih Eiffel Towers" (figure 1). The headframes of some mines have a height of 102–108 metres [34].

Currently, the programs of tours by functioning mining facilities most often include the open pits of JSC "Southern Mining-and-Processing Plant" or Hannivskyi open pit of PJSC "Northern Mining-and-Processing Plant" (figure 2).

Regarding mining complexes, most tourists prefer to go down to the depths of the earth, but it is very difficult to agree on safety issues with enterprises. Visiting surface mining complexes with a climb to the top of pitheads looks more promising in the tourist context. Among the working facilities, the "Yuvileyna" and "Kryvorizka" mines have the best opportunities for this.

The advantages and disadvantages of each of the working objects are presented in the table. Since there is a large number of mining facilities in the city, it was decided to focus on the

Table 1. Analysis of existing suitability for tourism of functioning mining facilities.

Name of the object	Positive features for tourism	Negative features for tourist activity
	Open pits	
Open pit of JSC “Southern Mining-and-Processing Plant”	• availability of 2 equipped covered observation decks; • availability of convenient entrances; • next to one of the observation decks there is a repair shop for truck vehicles, this allows to see the large-sized equipment relatively close; • relative proximity to the administrative centre of the city; • the original shape of the career is heart-shaped; • significant morphometric parameters; • facility of the ERIH network; • the quarry is a part of the structure of the enterprise, which was the first mining and beneficiation enterprise in the territory of the former USSR.	• the need to coordinate a visit to the facility with the management of the enterprise; • lack of toilets; • lack of a point of sale of souvenir products;
Hannivsky open pit of the PJSC “Northern Mining-and-Processing Plant”	• the possibility of free access; • considerable length – 5.8 km;	• located in the remote northern part of the city; • there is no equipped indoor area for visiting; • lack of toilets
	Mines	
“Yuvileyna” Mine	• one of the highest headframe in the city with a height of 108 metres; • most of the lifting is carried out in the elevator; • a wonderful panorama of the northern part of the city;	• the need to coordinate a visit to the facility with the management of the enterprise; • location in the relatively remote northern part of the city
“Kryvorizka” mine	• one of the highest headframe in the city with a height of 102 metres; • ascent is carried out in an elevator; • a wonderful panorama of the central part of the city; • located close to the administrative centre of the city	• the need to coordinate a visit to the facility with the management of the enterprise

Figure 1. The panorama of mining landscapes and mine's dills in Kryvyi Rih (photographed by Volodymyr L. Kazakov from the headframe of the Hihant-Hlyboka mine).

two main facilities, which are the most represented in excursion programs, when analysing the advantages and disadvantages. At the same time, the attention was focused precisely on the existing positive and negative features. The topic of military influence was not raised, as we believe it will be necessary to make a separate study after the end of hostilities.

In addition to the objects of the active mining industry, tour programs in Kryvyi Rih include abandoned mining objects that have formed various man-made landscapes – flooded quarries, dumps, failure zones and other specific objects. These objects are freely accessible for tourists, and some of them could be an excellent springboard for the implementation of various revitalization projects. The advantages and disadvantages of each of these objects are also presented in the table 2.

Some of these objects are shown in the figure 3.

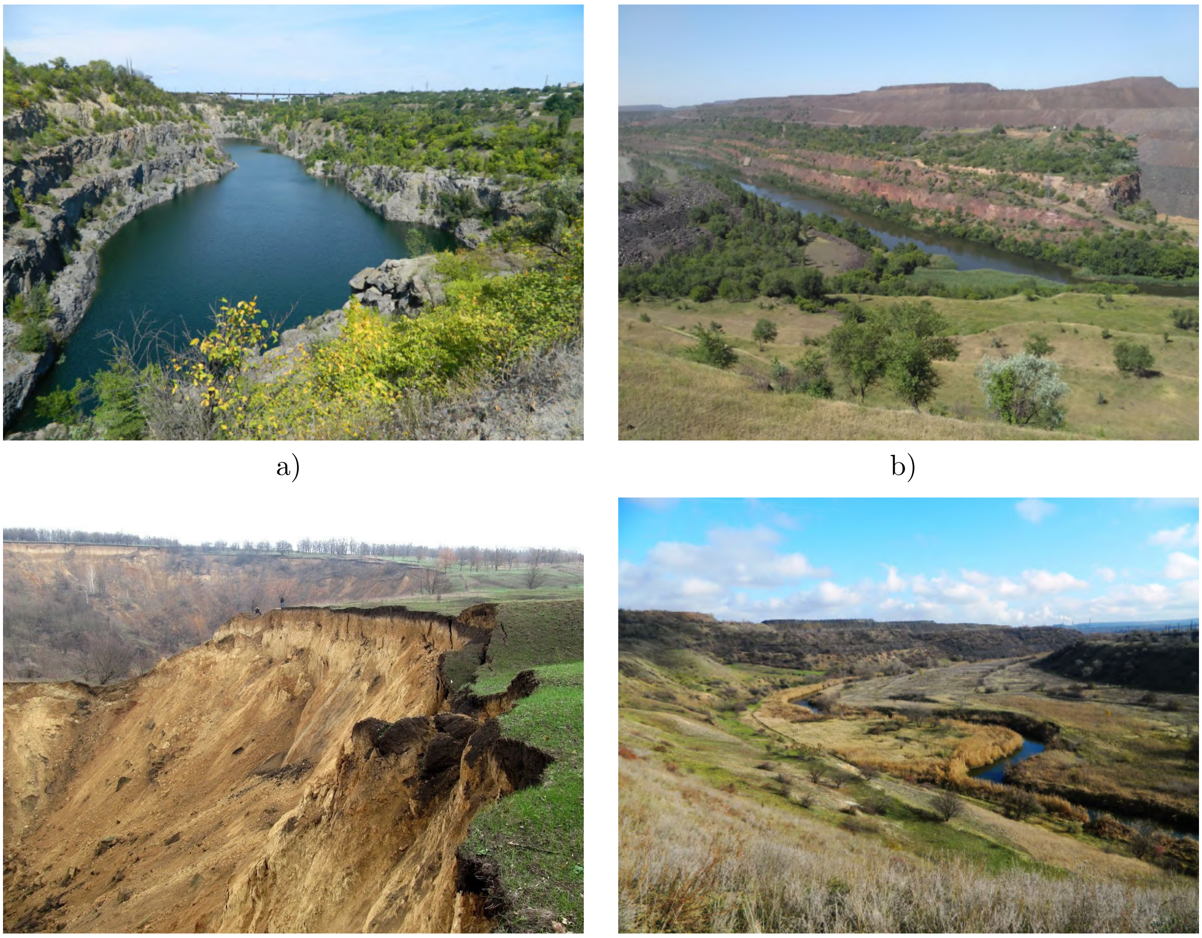
In addition to operating mining facilities and various landscapes, tour programs include auxiliary facilities:

- Open-air museums of mining equipment of PJSC "Northern Mining-and-Processing Plant" (figure 4) and the Mining Department of PJSC "ArcelorMittal Kryviy Rih", where a variety of mining equipment is presented: dump trucks, belt conveyors, magnetic separators, etc. Both of these facilities are included in the ERIH network;
- Museums of labour glory of mining-and-processing plants: Inguletskyi, Southern, Central and Northern ones (figure 5). They reveal the history of the creation and development of

Figure 2. Hannivskyi open pit of PJSC "Northern Mining-and-Processing Plant" (photographed by Volodymyr L. Kazakov).

enterprises, which is reflected in the main documents and photographic materials. You can see reduced samples of the machinery that works at the plants. Some museums have mock-ups of quarries that show installations of the production process. On TV screens, you can see the production process in quarries in real time, including blasting;

- Geological and Mineralogical Museum of Kryvyi Rih National University. This museum has a rich collection of rocks and minerals from around the world. Its entire collection of rocks was included in the State Register of Scientific Objects of National Heritage by a resolution of the Cabinet of Ministers of Ukraine;
- The Training and Course Centre of Kryvyi Rih Iron Ore Plant, which is a unique training ground – a model of the mine workings, located at a 3-metre-depth. Future miners are trained here, and tourists can get to know the essence of mining work, using mining equipment (scraper winch, jackhammer, drill, etc.). Mining horizons are simulated here, where samples of real equipment operated at the enterprise are located, as well as a camera for the temporary stay of miners in case of emergency situations (figure 6);
- 3D video gallery, the object is indirectly related to mining tourism, as it is located in Europe's largest flower clock. And it is here that they show films in 3D format about the history of the city, which is directly related to the formation of the mining industry.



a) b) c) d)

Figure 3. Different types of mining landscapes in Kryvyi Rih (photographed by Volodymyr L. Kazakov (a, b, d) and D. Antonov (c)): a) Karachunivskyi flooded granite quarry; b) the panorama of man-made landscapes from the Burshchytsky dump; c) the failure zone near the Ordzhonikidze mine; d) Kryvyi Rih Grand Canyon.

Table 2: Analysis of existing suitability for tourism of mining landscapes.

Name of the object	**Positive features for tourism**	**Negative features for tourist activity**
	Flooded quarries	
Oktyabrskyi granite quarry	• significant dimensions and depth make it possible to organize various types of water activities: swimming; boating, SUP-boarding, diving; • aesthetically attractive landscapes	• spontaneous recreation; • lack of small infrastructure facilities (toilets, garbage cans, information signs)

Continued on next page

Table 2 – continued from previous page

Name of the object	Positive features for tourism	Negative features for tourist activity
Karachunivskyi granite quarry	• location near one of the largest man-made waterfalls of Ukraine; • significant dimensions and depth make it possible to organize various types of water activities: swimming; boating, SUP-boarding, diving; • aesthetically attractive landscapes	• the presence near the dam of the Karachunivskyi reservoir, which was destroyed during rocket fire; • spontaneous recreation; • lack of small infrastructure facilities (toilets, garbage cans, information signs); • lack of convenient entrances
	Dumps	
Burshchytskyi dump	• a wonderful panoramic view of the city; • a gentle rise; • the possibility of inspecting the objects of the current industry (quarry, dump of PJSC "ArcelorMittal Kryvyi Rih") • location of industrial heritage sites nearby – the remains of the mine No. 5; Belelyubskyi bridge; remnants of the rolling railway of Hdantsivskyi Iron Foundry, etc.; • repeated practice of conducting both daytime and evening excursions to the dump; • significant relative height – about 60 metres; • the object was repeatedly filmed in Ukrainian travel shows	• lack of equipped approach to the object; • the presence of a solid household waste landfill next to the object; • lack of small infrastructure facilities (toilets, garbage cans, information signs)
Petrivskyi dump	• a wonderful panoramic view of the city; • the possibility of inspecting objects of active industry (quarry, dump of the Central Mining-and-Processing Plant) and industrial heritage (Shmakivska mine, built in 1886); • availability of convenient entrances to the facility • an organized celebration of the New Year was held at the object for several years in a row;	• lack of equipped approach to the object; • the ascent is stony and quite steep; • lack of small infrastructure facilities (toilets, garbage cans, information signs)

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Table 2 – continued from previous page

Name of the object	Positive features for tourism	Negative features for tourist activity
	• the locals regularly organize actions to plant trees for the purpose of landfill reclamation	
	Failure zones	
The failure zone near the Kozatska mine	• ccale forms; • nearby is the active two-hole superstructure of the Kozatska mine • the uniqueness of the object; • availability of convenient entrances to the facility; • a significant educational function from the point of view of sustainable development	• located in the remote northern part of the city; • lack of small infrastructure facilities (toilets, garbage cans, information signs);
The failure zone near the Ordzhonikidze mine	• Scale forms; • the uniqueness of the object; • located in the ore field of the oldest operating mine in Kryvyi Rih (Ordzhonikidze mine was founded in 1934 and operates up to this day); • availability of convenient entrances to the facility	• located in the remote northern part of the city; • landslide processes are not fully completed; • lack of small infrastructure facilities (toilets, garbage cans, information signs)
	Specific mining objects	
Kryvyi Rih Grand Canyon	• a unique formation that has no analogues in Ukraine; • a wonderful panoramic view of man-made landscapes; • availability within walking distance of the site of historic mines formed in 1881 – dates of the beginning of iron ore development in the region	• sufficient distance from the administrative centre of the city; • lack of convenient entrances; • lack of toilets
Red lake	• proximity to the administrative centre of the city; • availability of convenient entrances to the facility; • uniqueness; • a significant educational function from the point of view of sustainable development	• lack of toilets

A number of factors influence the direct inclusion of this or that object in the tour program:

- immediate duration of the tour;
- season of the year;

Figure 4. Open-air museum of mining equipment of PJSC "Northern Mining-and-Processing Plant" (photographed by Volodymyr V. Kazakov).

- available weather conditions;
- by which means of transport and where the group is coming from and where it goes next;
- age of tourists;
- specific requests from tourists.

Based on this, a matrix was created for the inclusion of certain mining objects in tour programs (table 3).

The location of these objects within the city of Kryvyi Rih is shown on the map (figure 7).

Monitoring of the websites of domestic tourist operators confirms that since 2016 the offers of tours to Kryvyi Rih have appeared from the following tour operators: "Kraina UA", "Anga Travel", "Ukraine Incognita" (Kyiv), "Visit" (Lviv), "Navigator" Ukraine", "100% Rest" (Kharkiv), "Globe of Ukraine" (Zaporizhya), "Golden Trips" (Dnipro), as well as Odesa tourist hub and tourist centre "Ryba Andriy" (Dnipro), tourist clubs "Bidnyazhka" (Vinnytsya), "Good trip" and "Wild Tour" (Kyiv), tourist companies "Mandrivochka" (Mykolayiv) and "InGreen" (Poltava) and a number of travel agencies from the cities of Kropyvnytskyi, Mykolayiv, Kherson, Kremenchuk, Dnipro, Nikopol, etc., which position themselves exclusively in social networks (figure 8).

6. Conclusions

The development of mining tourism in Kryvyi Rih has all the resource possibilities, but the presence of a powerful resource is not a guarantee of effective tourism. Before this resource is consolidated into a quality tourist product, it must be brought to the proper level. For this, we offer the concept of 3R – reclamation – revitalization – rethinking.

Table 3. Matrix for including mining objects in tour programs.

The name of the object of mining tourism in Kryvyi Rih	***Type of tour***			
	Tours over the southern part of the city	***Tours over the northern part of the city***	***Tours in the winter period***	***Tours for school groups***
Open pit at JSC "Southern Mining-and-Processing Plant"	+		+	+
Hannivskyi open pit of PJSC "Northern Mining-and-Processing Plant"		+		
Ground part and headframe of the mine "Yuvileyna"		+		
Ground part and headframe of the mine "Kryvorizka"	+			
Oktyabrskyi flooded granite quarry		+		+
Karachunivskyi flooded granite quarry	+			+
Burshchytskyi dump	+			+
Petrivskyi dump		+		
The failure zone near the "Kozatska" mine		+	+	
The failure zone near the Ordzhonikidze mine		+	+	
Kryvyi Rih Grand Canyon	+			
Red lake	+	+	+	+
Open-air museum of mining equipment of the Mining Department of PJSC "ArcelorMittal Kryvyi Rih"	+		+	+
Open-air museum of mining equipment of PJSC "Northern Mining-and-Processing Plant"		+	+	+
The Museum of Labour Glory of the Southern Mining-and-Processing Plant	+		+	+
The Museum of Labour Glory of the Northern Mining-and-Processing Plant		+	+	+
The Museum of Labour Glory of the Central Mining-and-Processing Plant		+	+	+
The Museum of Labour Glory of Inguletskyi Mining-and-Processing Plant	+		+	+
Geological and Mineralogical Museum of Kryvyi Rih National University	+		+	+
Training and Course Centre of Kryvyi Rih Iron Ore Plant		+	+	+
3D video gallery	+		+	+

Reclamation. Its goal is to restore the productivity of areas disturbed by the mining industry and return them to different uses. This involves carrying out a complex of engineering, mining, reclamation, agricultural and forestry works. Restoration of lands disturbed by mining operations is a complex process of landscape regeneration and is carried out in several stages:

- preparatory, on which mining spaces are studied and typified and, due to their specificity, promising opportunities for their economic use are determined;

Figure 5. Museums of labour glory of JSC "Southern Mining-and-Processing Plant" (photographed by Viktoriia S. Patsiuk).

- the stage of mining reclamation is the engineering preparation of the territory for various types of further reclamation, and includes: surface planning; creation of slopes of optimal structure and parameters; regulation of the water regime; various amelioration measures; construction of access roads and other structures;
- the stage of biological reclamation and the transition to the targeted use of mining spaces, aimed at the final restoration of fertility and biological productivity of disturbed lands, the implementation of forests and meadow plantations, the arrangement of the infrastructure of the planned space.

The reclamation of mining spaces and their involvement in the tourism sphere should be adjusted by knowledge about the structure, properties and technology of operation of a specific object and all possible directions of improvement or rational changes in its condition. Therefore, for each landscape, its own development and optimization trend is recommended. Thus, for example, the mining landscapes of the Oktyabrskyi granite quarry and dump, due to long-term self-development and spontaneous recreation, do not require special methods of reclamation, it is enough only to control the volume of water inflows, the ecological quality of the water body and cultivate the spaces, create tourist infrastructure. At the same time, relatively chaotic reclamation is taking place at the landfills of the city, especially at Petrivskyi, by local residents.

Revitalization is a process aimed at the complex transformation of depressed industrial facilities and territories for their functional reformation in order to improve the social living conditions of the population. In Kryvyi Rih in 2019 "Urban hackathon" took place, within which framework the prospects of five industrial facilities of the city were discussed. Four

Figure 6. Lithuanian students during an excursion to the Training and Course Centre of Kryvyi Rih Iron Ore Plant (photographed by Viktoriia S. Patsiuk).

of these mining-related objects are: the “Artem-2” mine, premises and pithead of the mine “Ventylyatsiyna-3”, the premises of the former Lenin Mining Administration, and Burshchytskyi dump.

Expert groups prepared options for the revitalization of these objects. On the site of the former management office of the Lenin mine it is proposed to create a youth centre, on which roof it is planned to create an observatory with a relaxation area. Four floors of the building can be thematic ones, where there will be rooms for work and rest, an art hub, a hostel, a multifunctional centre, a thematic museum with the involvement of moving and interactive elements, exhibition halls, etc. Another option was to create a social centre “InTerny” on the basis of this building. The task of the centre is to help the most affected categories of the population.

On the territory of the mine “Ventylyatsiyna-3” it is proposed to create an active leisure centre “StreetTown”. The buildings offer the following locations: an administrative zone, a food zone, a sanitary zone, an indoor skate park, a trampoline, dance floors. It is also planned to place speleological training locations in the mine shafts and a climbing wall on the wall of one of the buildings. Near the buildings a small parking lot, a skate park, a bicycle area and a fountain with iron fish as a symbol of the iron ore basin are planned to be created [34].

On the territory of Burshchytskyi dump, the creation of a landscape-industrial park “Vidval” is proposed. The peculiarity of this project is the zoning of the territory into several blocks:

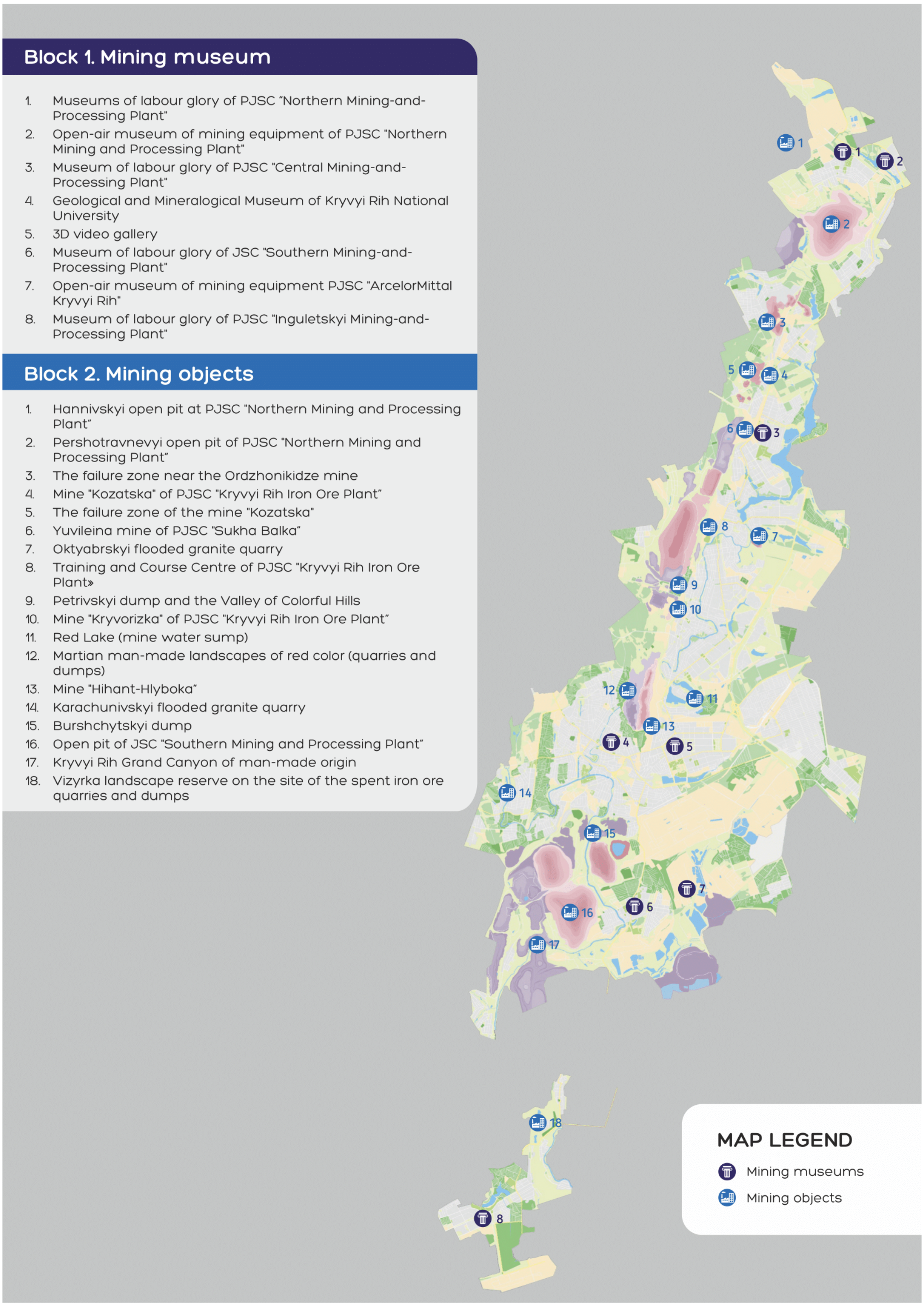

Figure 7. Map of Kryvyi Rih mining sites included in the tour programmes.

Figure 8. A group of tourists on the observation deck of the open pit at JSC "Southern Mining-and-Processing Plant" (photographed by Volodymyr L. Kazakov).

1) sports – since the Ingulets river is nearby, it is planned to equip a zone for riding on water vehicles, as well as to set aside a zone for dirt track and a motorcycle track; 2) recreational – it is planned to lay eco-trails on the slopes of the dump; 3) infrastructural – here it is planned to arrange entrances and parking lots, allocate the territory for a camping site, as well as create a food and picnic area; 4) animated – it is planned to create the inscription "Crooked Horn" on the top of the dump, to organize a park of thematic gabions nearby, and also to conduct a cableway across the Ingulets river to the nearby dump.

The territory of the "Artem-2" mine is the most promising for revitalization. It is proposed to create a multifunctional park of industrial culture (PIK) "Shakhta". The main attraction of the object should be the inclined shaft, which will be used to descend to the mine. On the walls of the shaft it is proposed to create a historical engraving of the development of metallurgy in the city. It is proposed to create a museum of mining equipment in the premises of the mothballed mine. Other premises can be classified as small laboratories and workshops with master classes. In the surrounding area, it is proposed to create an open-air museum of mining equipment, as well as a sports sector with existing playgrounds, courts, a climbing wall, etc. [34].

In addition, in Kryvyi Rih there are also significant prospects for revitalization of the "Higant-Hlyboka" mine pit, which offers a wonderful panorama of the city, the "Pobeda" mine, the flooded Oktyabrskyi and Karachunivskyi granite quarries, as well as Vizyrka landscape reserve, which was created on the basis of 3 exhausted iron ore quarries. On the territory of each of these objects, it is possible to create landscape and industrial park areas, expanding the range of possible areas of recreation and provision of services.

Rethinking. The organization of innovative tourist activities for old industrial regions requires a radical rethinking not only of the resource potential of the territory, but also of methods and approaches to conducting economic (including pure tourist) activities in these regions and realizing the need for total diversification of the economy of these territories not only from the point of view of branching out their production structure, namely due to the growth of the segment of the sphere of services and creative industries.

It is necessary to radically change the perspective of the assessment of mining objects, that is, to perceive the mining heritage not only as an echo of the past, and functioning mining enterprises – not only as a raw material appendage, but to realize that both the heritage and the operating industry have a significant potential for educational and cognitive direction.

It is the revaluation of directions for the use of mining objects and landscapes that is an important factor not only in the development of the tourism potential of mining territories, but also in raising the level of the industrial culture of the population. All this will generally have a significant positive economic, social and humanitarian effect.

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References

[1] 2018 Proekt Zakonu pro Stratehiiu staloho rozvytku Ukrainy do 2030 roku URL https://w1.c1.rada.gov.ua/pls/zweb2/webproc4_1?pf3511=64508
[2] Postma A, E C and Spruyt E 2017 **3**(1) 13–22 URL https://doi.org/10.1108/JTF-10-2015-0046
[3] Denysyk H I and Zadorozhnia H M 2013 *Pokhidni protsesy ta yavyshcha v landshaftakh zon tekhnohenezu* (Vinnytsia: Edelveis i K)
[4] Leonard L 2016 *Local Economy* **31**(1-2) 249–263 URL https://doi.org/10.1177/0269094215621875
[5] Herrera-Franco G, Apolo-Masache B, Escandón-Panchana P, Jácome-Francis K, Morante-Carballo F, Mata-Perelló J and Carrión-Mero P 2022 *Geosciences* **12**(9) 322 ISSN 2076-3263 URL https://doi.org/10.3390/geosciences12090322
[6] Jonsen-Verbeke M 1999 *Tourism Geographies* **1**(1) 70–85 URL https://doi.org/10.1080/14616689908721295
[7] Herdiansyah H, Utami M U and Haryanto J T 2018 *Jurnal Perspektif Pembiayaan dan Pembangunan Daerah* **6**(2) 167–180 URL https://doi.org/10.22437/ppd.v6i2.5441
[8] Ilkovičová Ĺ and Ilkovič J 2022 *Land* **11**(6) 936 ISSN 2073-445X URL https://doi.org/10.3390/land11060936
[9] Różycki P and Dryglas D 2017 *Acta Montanistica Slovaca* **22**(1) 58–66 URL https://actamont.tuke.sk/pdf/2017/n1/6rozycki.pdf
[10] Nita J and Myga-Piątek U 2015 *Bulletin of Geography. Physical Geography Series* (7) 139–156 URL https://doi.org/10.2478/bgeo-2014-0007
[11] Cole D 2004 *Journal of Sustainable Tourism* **12**(6) 480–494 URL https://doi.org/10.1080/09669580408667250
[12] Edwards J A and i Coit J C L 1996 *Annals of Tourism Research* **23**(2) 341–363 ISSN 0160-7383 Heritage and tourism URL https://doi.org/10.1016/0160-7383(95)00067-4
[13] Jelen J 3918 *Czech Journal of Tourism* **7**(1) 93–105 URL https://doi.org/10.1515/cjot-2018-0005
[14] Kadlec M and Svoboda M 2007 *Památková péče, cestovní ruch a veřejná správa [Monument care, tourism and public administration]* (Praha: Ministerstvo pro místní rozvoj ČR) URL http://www.mmr.cz/getmedia/71687f46-21f8-4e70-8b5c-afb6ab19ad38/GetFile7_1.pdf
[15] Garofano M and Govoni D 2012 *Geoheritage* **4**(1) 79–92 ISSN 1867-2485 URL https://doi.org/10.1007/s12371-012-0055-3
[16] Gürer A, Gürer Ö F and Sangu E 2019 *Arabian Journal of Geosciences* **12**(23) 734 ISSN 1866-7538 URL https://doi.org/10.1007/s12517-019-4927-6

[17] Singh R S and Ghosh P 2021 *International Journal of Geoheritage and Parks* **9**(2) 172–181 ISSN 2577-4441 Exploration of Geoheritage, Geoparks and Geotourism URL https://doi.org/10.1016/j.ijgeop.2021.02.007

[18] Rybár P and Hronček P 2020 *Geotourism/Geoturystyka* (50-51) 3 URL https://doi.org/10.7494/geotour.2017.50-51.3

[19] Rybár P and Štrba L 2016 Mining tourism and its position in relation to other forms of tourism *GEOTUR 2016: International Conference on Geotourism, Mining Tourism, Sustainable Development, and Environmental Protection* ed Ugolini F, Marchi V, Trampetti S, Pearlmutter D and Raschi A (IBIMET-CNR) pp 7–12

[20] Leonard L and Lebogang T 2018 *Sustainable Development* **26**(3) 206–216 URL https://doi.org/10.1002/sd.1695

[21] Schejbal C 2016 *Montánní turismus [Mining tourism]* (Ostrava: VŠB-TU Ostrava)

[22] Caamaño-Franco I and Suárez M A 2020 *Land* **9**(11) 404 ISSN 2073-445X URL https://doi.org/10.3390/land9110404

[23] Lamparska M 2019 *Journal of Geography, Politics and Society* **9**(2) 57–68 URL https://doi.org/10.26881/jpgs.2019.2.06

[24] Byström J 2022 *Polar Record* **58** e40 URL https://doi.org/10.1017/S003224742100019X

[25] Ruiz Ballesteros E and Hernández Ramírez M 2007 *Tourism Management* **28**(3) 677–687 ISSN 0261-5177 URL https://doi.org/10.1016/j.tourman.2006.03.001

[26] Brereton D, Memmott P, Reser J, Buultjens J, Thomson L, Barker T and Chambers C 2007 Mining and indigenous tourism in Northern Australia Tech. rep. CRC for Sustainable Tourism Pty Ltd URL https://www.csrm.uq.edu.au/media/docs/345/mining_indigenous_tourism_northern_australia.pdf

[27] López M I and Pérez L 2013 *EURE (Santiago)* **39** 199–230 ISSN 0250-7161 URL https://doi.org/10.4067/S0250-71612013000300009

[28] Liccardo A, Mantesso-Neto V and Do Nascimento M A L 2020 Mining Heritage as Geotourism Attractions in Brazil *The Geotourism Industry in the 21st Century* ed Sadry B N (New York: Apple Academic Press) pp 117–144 ISBN 9780429292798 URL https://doi.org/10.1201/9780429292798-5

[29] Nicklin M W 2022 This former coal mining region now fuels green tourism URL https://www.nationalgeographic.com/travel/article/this-former-coal-mining-region-now-fuels-green-tourism

[30] Kazakov V L 2001 Na shliakhu do povnoho vyvchennia hirnychopromyslovykh landshaftiv kryvbasu *Teoretychni, rehionalni, prykladni napriamy rozvytku antropohennoi heohrafii ta heolohii: mater. III mizhnar. nauk. konfer* pp 35–47

[31] 2013 Prohrama rozvytku promyslovoho turyzmu v misti Kryvyi Rih na 2013–2015 roky [Program of industrial tourism development in Kryvyi Rih for 2013–2015]

[32] 2016 Prohrama rozvytku promyslovoho turyzmu v misti Kryvyi Rih na 2016–2020 roky [Program of industrial tourism development in Kryvyi Rih for 2016–2020] URL http://krt.dp.ua/files/pdf/The_program_of_development_of_industrial_tourism_2016--2020.pdf

[33] 2023 European route of industrial heritage - ERIH URL https://www.erih.net/

[34] Patsiuk V S and Kazakov V L 2017 Chy mozhe industrialnyi turyzm zminyty oblychchia Kryvoho Rohu? [Can industrial tourism change the face of Kryvyi Rih?] *Urban Ukraine: in the epicenter of spatial changes* ed Mezentsev K, Oliinyk Y and Mezentseva N (Phoenix) pp 378–393

Assessment of military destruction in Ukraine and its consequences using remote sensing

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Assessment of military destruction in Ukraine and its consequences using remote sensing

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Abstract. The article raises the problem of using Earth remote sensing data to collect evidence of damages caused by the military actions of the Russian army in Ukraine. The core data set obtained by deciphering aerial photographs reflects the general current and operational situation in the affected area, reducing the subjectivity and uncertainty of damage characteristics on the ground. Earth remote sensing data visualize visible damage to the environment, which can be recognized and assessed using images of different spectral bands with appropriate resolution. Among the damage caused to the environment as a result of hostilities, according to the Earth remote sensing data, it is possible to study: degradation of land resources, destruction of natural ecosystems by fires, destruction of structures (buildings) and structures. Satellite images with a very high resolution ($\leq$ 1 m) make it possible to quantify the degree of damage to the soil surface due to shell explosions: the amount of metal fragments and chemicals that have entered the soil, damage to the biological cover, etc. Images with a resolution of less than 30 meters in the short-wave infrared (SWIR) range allow to depict the devastating effects of forest and steppe fires caused by military actions. Using two different time frames, one before the fire and one after, will ensure the accuracy, objectivity and reliability of the evidence collected. These very high resolution Earth remote sensing images are used to investigate the destruction of structures (buildings) and constructions. The analysis of satellite images guarantees the diagnosis of the condition of the building in three degrees of destruction: completely destroyed, partially destroyed or not destroyed. In order to ensure the storage, quick search, analysis and visualization of all useful information obtained from the data of Earth remote sensing, it is necessary to use geoinformation systems.The proposed methodology for assessing military destruction is characterized by simplicity, accuracy and versatility, and does not require the use of expensive equipment.

1. Introduction

Constant armed conflicts on the planet throughout the entire existence of mankind lead to catastrophic consequences. So, by the end of 2021, almost 80 million people have lost their homes and been forcibly displaced around the world due to armed conflicts. The full-scale, unprecedented war unleashed by the Russian Federation on the territory of Ukraine since February 24, 2022, in terms of the scale of military operations, human casualties, destruction and material losses, has virtually no analogues since the Second World War. More than 30% of the territory of Ukraine suffered losses from war-related pollution, destruction, bombings, etc. In just half a year of war, the amount of losses from Russia's military aggression, confirmed by the World Bank, amounts to more than 340 billion dollars.

In connection with this, there is an urgent issue of receiving reparations and compensations from the aggressor country for the restoration and reconstruction of Ukraine. The amount and nature of reparations must be determined in accordance with the caused damage. That is why there is a need to measure and confirm war losses.

Such information is collected on the base of the analysis of tens of thousands of public reports from citizens, government, local authorities about loss and damage across the country, as well as on the basis of public sources. However, considering the scale of the damage, it is clear that we need to look for more modern and sophisticated forms of collecting evidence of damages for legal proceedings and lawsuits against the aggressor.

One of the most promising directions in this matter is the use of Earth remote sensing technologies. Aerospace images ensure the independence and persuasiveness of the evidence obtained due to the decryption of the data of ERS. Importantly, this baseline data set reflects the overall actual and operational situation of the damage zone, reducing the subjectivity and uncertainty of damage characterization on the ground.

This is facilitated by access to high-resolution images at various ranges and with a frequency of observation ranging from one to two weeks to daily monitoring.

Currently, in the literature, one can find a sufficient number of examples of the use of ERS methods in areas of armed conflicts in order to study the impact of their consequences on the geographical environment. Conventionally, all these studies can be divided into three areas: legal, applied and methodical.

Legal publications address various aspects of the use of Earth remote sensing data as evidence for legal claims. Most authors [1–3] point to the fact that the value that this unique form of evidence can have is still underutilized compared to its potential. The main problems associated with the use of aerial photographs as evidence in international criminal courts are the limited availability of relevant images, the cognitive bias of external organizations conducting the analysis of ERS as well as the lack of legal certainty in this area (there are no accepted forensic medical standards and methodologies).

As a result, in their works the authors consider various ways to overcome these difficulties, among which the main ones are the following:

- due to the digital and technological nature of satellite evidence, it is especially important to establish its accuracy, objectivity and reliability;
- the development of standardized methods of collecting, storing and interpreting the data of ERS is required;
- for the use of aerial photographs as evidence in courts, it is necessary for judges to be familiar with geospatial data technologies.

Scientific publications of an applied orientation demonstrate the attention of the world public to the monitoring of armed conflicts with the aim of analyzing the observance of human rights, tracking genocides, analyzing the migration of refugees, etc. As an example, we can cite the use of remote sensing data of time series (night lights) to study the development of the crisis and refugee flows after the "Arab Spring" [4]. By means of satellite analysis using Landsat 8 images (2013 and 2015), Sawalhah et al identified the impact of population growth and Syrian refugee settlements on rangeland degradation in Jordan [5].

Obtaining information in near real time provides an opportunity to develop rapid response measures in the provision of assistance and crisis management, as well as early warning systems to minimize civilian casualties in war zones [6].

The impact of armed conflicts on the ecological state of the geographical envelopes of Asia, Africa, and Latin America is considered by Hoffmann et al [2], Ordway [7], Shatnawi et al [8]. Thanks to information obtained from satellite images, researchers studied how military confrontation directly affected the physical environment during the war and the post-war period.

Today, there are examples of the use of ERS data to assess damages from military conflicts by international organizations, such as the United Nations, the World Bank, Amnesty International, etc. [9]. Thus, since 2003, the United Nations Satellite Center (UNOSAT) provides analysis of satellite images during humanitarian emergencies related to natural disasters, complex emergencies and military conflicts. As an example, we can cite the results of damage assessment of buildings in Kherson (Ukraine), based on images received from the WorldView-3 satellite. Analysis of images taken on October 14, 2022 revealed 88 buildings with visible damage. Of these, 4 are destroyed, 69 are substantially damaged, 4 are moderately damaged, and 11 are possibly damaged.

The methodical features of the use of ERS technologies during the monitoring of territories affected by the war were not left out of the attention of scientists. Most of the authors [10–13] note that damage assessment using satellite images is a complex, painstaking process that takes a lot of time and often requires site inspection.

In this regard, more and more researchers pay attention to the use of computer vision to identify different types of damage using aerial imagery. Using the previous stage of machine learning, it becomes possible to effectively apply the automated building damage classifier [12, 14]. As a practical embodiment of this approach, we can give an example of the development of the company "NeuroMarket" (Ukraine), which has created a neural network algorithm that can analyze the degree of damage caused to a building using images from satellites and drones.

Therefore, despite the significant interest in this problem in the scientific literature and world practice in the last 10 years, it should be noted that investigations on the study of environmental damage as a result of military actions are of a purely local, narrowly regional nature.

The objective of this research is to explore the potential application of Earth remote sensing techniques in areas affected by armed conflicts. The study aims to investigate and assess the impact of these conflicts on the geographical environment and the state's economy.

2. Methods

Different time satellite panchromatic and multispectral images with different resolutions have been used in the work (table 1). Image sources are open platforms *FIRMS, EO Browser, Google Earth PRO, USGS Earth Explorer and Maxar Technologies.* It is important that all the sources of the images are official and ensure the independence and persuasiveness of the evidence obtained through the decoding of satellite images. Image processing has been carried out in the open *Quantum GIS* environment.

3. Results and discussion

A full-scale war in Ukraine causes significant damage to the state of nature and the country's economy. According to the estimates of *the KSE Institute*, during just six months of the war, the amount of direct lesion to the economy of Ukraine from the damage and destruction of residential and non-residential buildings and infrastructure (in monetary terms) amounted to \$108.3 billion. Taking into account indirect losses (reduction in GDP, cessation of investments, outflow of labor, additional costs for defense and social support, etc.), this figure ranges from \$564 billion to \$600 billion. Determining all damages, documenting them, and assessing the

Table 1. General indicators of the satellites which images were used in the work and the types of the determined environmental damage.

№	Satellite	Spatial resolution (m)	Spectral bands	Periodicity of removal (day)	Type of environmental damage
1	Terra MODIS	250–1000	36	1–2	Spatio-temporal indicators of fires
2	Landsat 8	15, 30	11	16	Destruction of natural ecosystems by fires
3	Sentinel 2A, 2B	10, 20, 60	13	5	Destruction of natural ecosystems by fires
4	GeoEye	0,46	pan	1	Degradation of land resources and destruction of submitted and constructions
5	WorldView–3	0,31	pan	1	Degradation of land resources and destruction of submitted and constructions

scope for obtaining further reparations and compensations from the aggressor country is a very important task for various government and scientific structures and organizations.

Earth remote sensing data visualize a variety of environmental damage. But at the same time, it should be borne in mind that this is a visual monitoring method and it can be used only to assess those damages that can be visually recognized and evaluated using images of different spectrum ranges and the corresponding spatial resolution.

Thus, of all the environmental damage caused by hostilities, the following can be studied with the help of the data of ERS: degradation of land resources, destruction of natural ecosystems by fires, and destruction of structures (buildings) and constructionls. Let's consider each of these damages separately.

A. Degradation of land resources

One of the most negative and destructive consequences of military operations is the disruption of the soil ecosystem. Millions of exploding projectiles leave behind thousands of square kilometers of excavated Ukrainian land, contaminated with fragments of metal and chemicals.

Satellite images with a very high spatial resolution ($\leq$ 1 m) make it possible to estimate the extent of disturbances in the surface soil layer. Figure 1 shows satellite images of fields in the Donetsk region, taken before and after the intervention of the Russian invaders. In the picture taken after the beginning of the military aggression, we see agricultural fields dotted with hundreds of artillery shells. Funnels of such density almost completely destroy the soil cover and make it unsuitable for use.

Shelling was carried out with the following types of weapons:

- 82 mm — mortars with 82-mm fragmentation and high-explosive fragmentation mines;
- 120 mm — "Grad" installations, field and self-propelled howitzers;
- 152 mm — mortars with 152 mm shells, guns and howitzers;
- 220 mm — rocket salvo fire system "Hurricane".

The size of the recess in the soil corresponds to the caliber of the projectile: 220 mm – the diameter of the funnel is about 7 m, 152 mm – 4–6 m, 120 mm – 2.5–3.5 m, 82 mm – about

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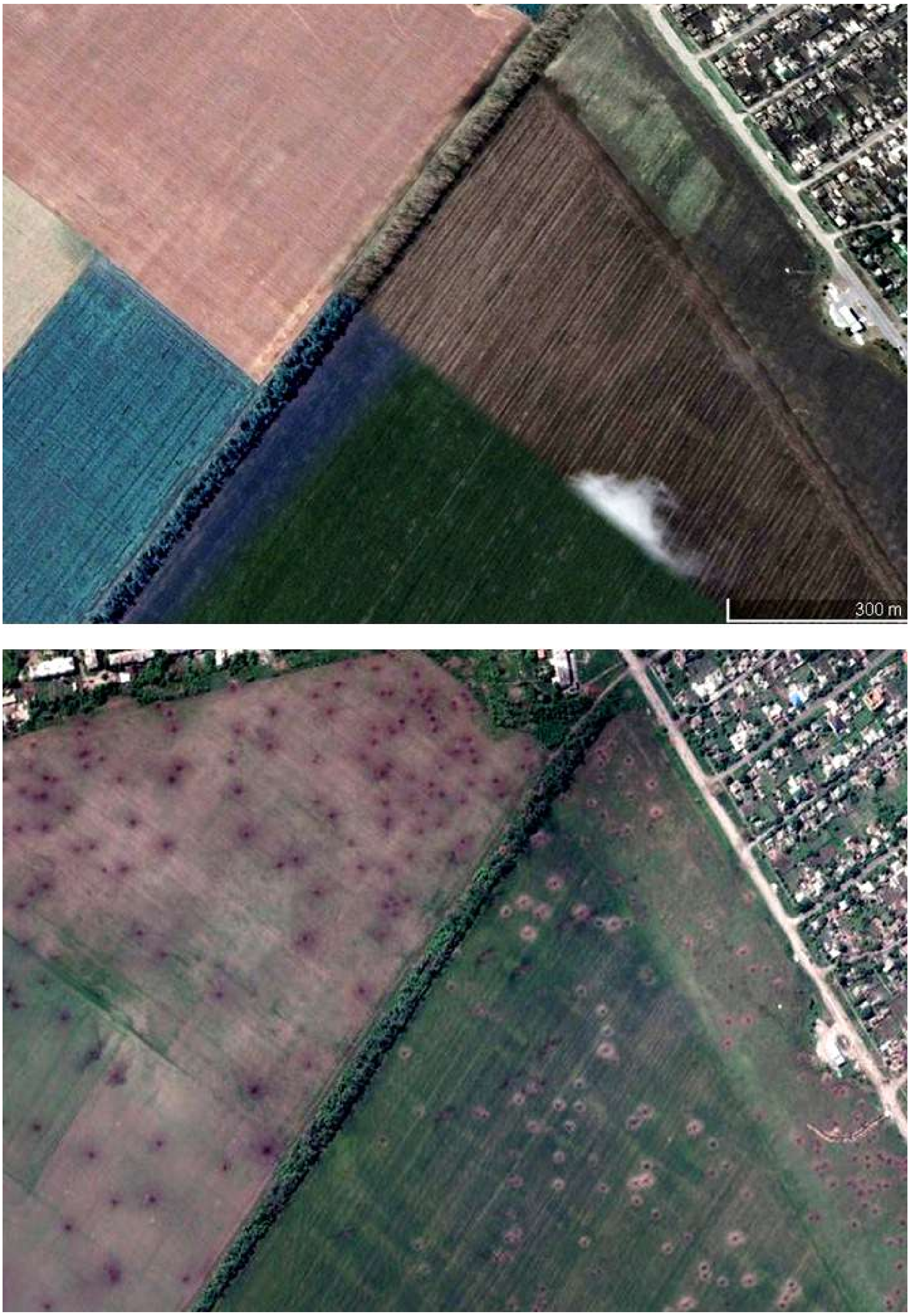

Figure 1. Satellite image of agricultural land near the town of Lyman (Donetsk region). 48.988056. 37.833333. Above – 8.05.21. Below – 26.05.22. [Source: Satellite Image 2022 Maxar Technologies, EPA].

1 m [15]. Using the scale of the picture, you can easily determine not only the number of shelling, but also the caliber of the projectiles.

Figure 2 shows an example of soil ecosystem disturbance calculations. On a plot of agricultural field near the town of Lyman (Donetsk region) with an area of 0.06 square km (200 m x 300 m) there are 71 funnels from explosions. Among them: 6 – from the caliber of 220 mm, 40 – 152 mm, 12 – 120 mm and 13 – 82 mm (table 2).

Artillery projectiles produce fragments weighing 1 gram or more: caliber 82 mm – 1,200–1,550 pieces, 120 mm – 1,600–2,350 pieces, 152 mm – 2,700–3,500 pieces, respectively [16]. Using these data, it is possible to calculate that on a certain section of the field with an area of 0.06 square

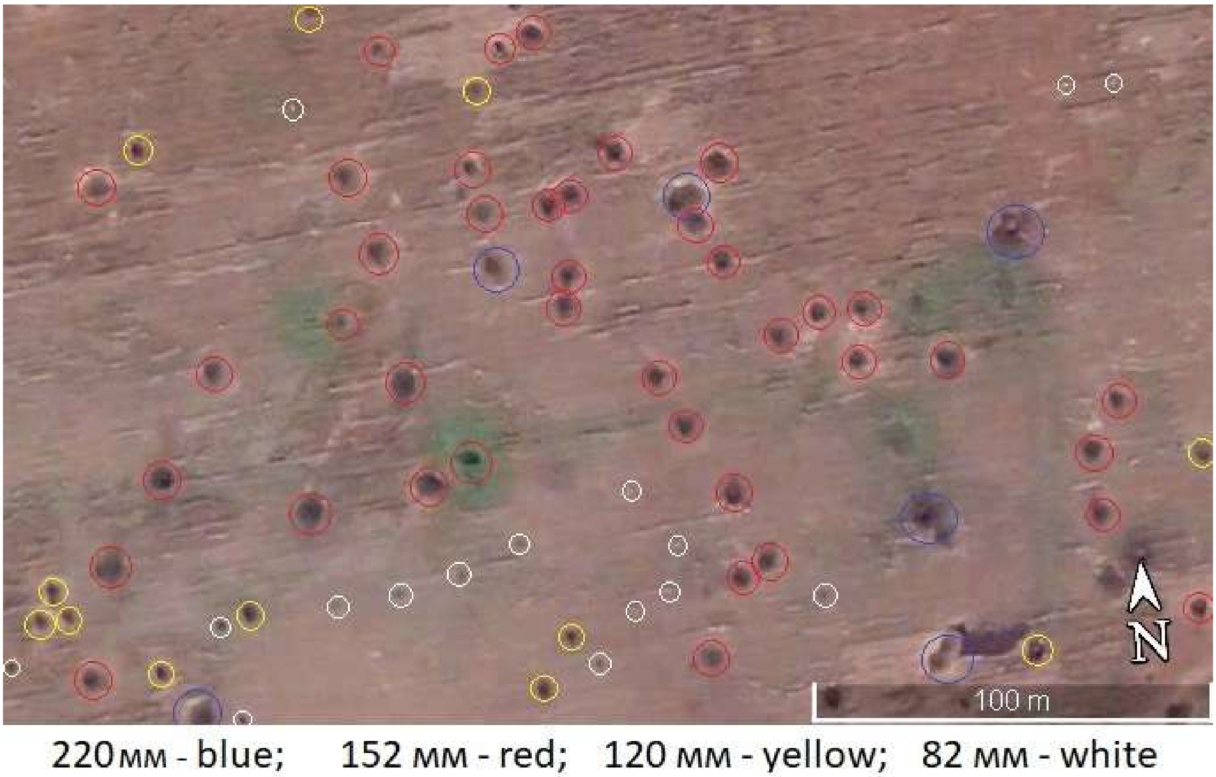

Figure 2. Counting funnels from projectile explosions of various calibers in a field near the settlement of Pisky (Donetsk region). 48.075556. 37.664167. [Source: Satellite Image 2022 Maxar Technologies, EPA].

Table 2. Indicators of soil degradation of the specified territory.

Ammunition caliber, mm	Number of funnels	Number of projectile	Amount of chemical elements, kg				Amount of explosive, kg
			Fe	C	S	Cu	
220	6	23000	570	8.8	9.2	4.4	235
152	40	124000	1500	23	28	10	210
120	12	24000	210	3	4	1.5	25
82	13	18000	38	0.6	0.65	0.25	5
In general	71	189000	2318	35.4	41.85	16.15	475

km, almost two hundred thousand metal fragments with a total weight of about 2.5 tons fell into the soil.

These metal fragments are dangerous. In addition to iron and carbon, they also contain sulfur and copper [15, 16]. Taking into account the number of projectiles and their caliber, it is possible to calculate the total amount of chemicals that have entered the environment in the studied area – this is about 35 kg of carbon, 32 kg of sulfur and 16 kg of copper (table 2).

Chemical elements that have entered the soil are very dispersed. This will contribute to their rapid entry into the soil, and from there into surface water, and in this way they enter the cycle of environmental substances and will be included in trophic chains. So, for example, copper is a heavy metal, individual compounds of which can be quite toxic [17].

In addition, all modern high-explosive and high-explosive fragmentation projectiles release an average of 1.2–1.5 cubic meters of soil per 1 kilogram of explosive [17]. Based on this, as a result of the explosion of 71 shells, the mass of the explosive substance (amotol, hexane) totaled 475 kg. As a result, almost 700 m^3 of soil was uprooted, disrupting its biological cover.

Such destruction of the soil cover together with other negative factors make the territories of rural lands unsuitable for use. It takes hundreds of years to restore land resources from pollution. Even now, in 300 days of the war, according to preliminary estimates by experts, no less than 10 billion dollars will be needed to restore Ukrainian land.

At the same time, it should be taken into account that satellite images can serve as indirect evidence of the negative consequences of shell explosions on the environment.During the detonation of amotol and hexogen, a number of chemical compounds are formed – carbon monoxide, carbon dioxide, nitrogen oxide, nitrogen dioxide, formaldehyde, cyanic acid vapors, nitrogen, as well as a large amount of identified and unidentified toxic organics [17]. It is impossible to calculate even an approximate number of these emissions. Under their influence, surrounding soils, wood, and structures are oxidized.

B. Destruction of natural ecosystems by fires

Monitoring of fire areas is one of the most common areas of practical use of data from ERS So, for example, *NASA* has created *Fire Information for Resource Management System (FIRMS)* scale fires on the Earth's surface. The corresponding site shares near-real time data on active fires from the Moderate Resolution Imaging Spectroradiometer *(MODIS)* aboard the *Aqua and Terra* satellites and the *Visible Infrared Imaging Radiometer Suite (VIIRS)* aboard *S-NPP* and *NOAA 20* (figure 3).

The resolution of Terra MODIS infrared channels is 1 km/pixel. This means that each detected fire cell is displayed as a point in the center of a 1 km × 1 km pixel. It is practically impossible to determine the objects of fires and assess the consequences of fires in images with such a spatial resolution. They can be used only to determine the spatio-temporal indicator of the fire: place and time of occurrence. In addition, with the help of these images, it is possible to record the total number of fires on a daily basis. Thus, most of the fires recorded by the Terra satellite took place in the period from mid-summer to the beginning of autumn 2022 in the territory of forests, forest belts and steppes, mainly in the zone of combat clashes.

For a detailed analysis of fires and their consequences, satellites with a resolution of less than 30 meters should be used (Landsat 8, Sentinel 2A, 2B, etc. – see table 1).

Among all natural ecosystems of Ukraine, forests suffer from hostilities mostly. The massive use of artillery and strike aircraft against military and infrastructure facilities in and near forests causes forest fires, which in dry conditions destroy tens and sometimes hundreds of square kilometers of forest. So, for example, according to the official information of the leadership of Ukraine, almost three million hectares of forests were destroyed during the eight months of the war as a result of shelling by Russian troops on the country's territory.

Mapping the destructive effects of wildfires is most effective in the short-wave infrared (SWIR)

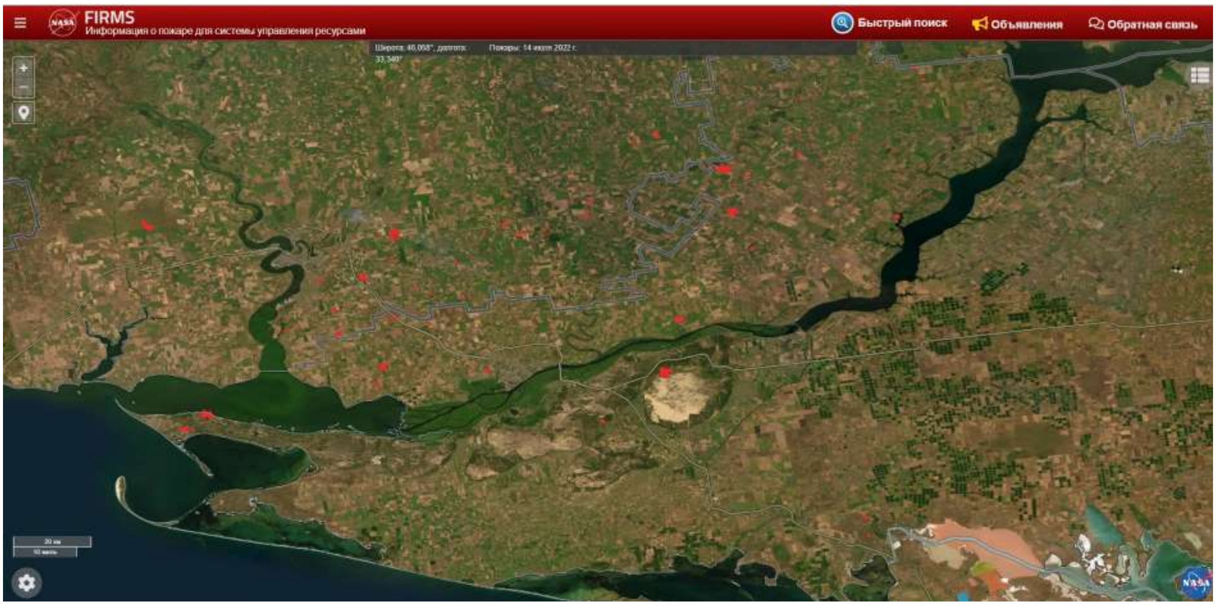

Figure 3. Forest and field fires in the Kherson and Mykolaiv regions. 14.07.22. [Satellite: Terra MODIS. Source: firms.modaps.eosdis.nasa.gov].

Figure 4. Satellite image of the Kinburn Peninsula (Ukraine). 23.07.22. Areas of burnt forests are of brown colour [Satellite: Sentinel-2. SWIR range. Source: EO Browser].

range. For the Sentinel 2A satellite, this is a combination of channels B12, B8A, B04. In this composite, vegetation is shown in shades of green, and recently burned land is shown in brown (figure 4).

For a semi-automated method of calculating the area of fire-destroyed forests, it is possible to process a raster image in the environment of a geographic information system. Figure 5 shows an example of raster classification of a satellite image of the Nedohirsky Forest in the QGIS program with subsequent area determination using the program's functionality.

Figure 5. Satellite images of the Nedogorsky forest (landscape reserve "Inguletsky", Velyka Oleksandrivka, Kherson region). On the left – 21.07.15. Case – 22.05.31. [Satellite: Sentinel-2. SWIR range. Source: EO Browser].

In order to record and calculate the consequences of forest fires, it is necessary to have two pictures taken at different times: one before the fire, the other after (figure 5). In this way, we can ensure the accuracy, objectivity and reliability of the collected evidence. The necessary combination of channels for capturing the analyzed terrain can be obtained using the EO Browser cloud platform. The functionality of the platform allows us to measure the area of destroyed forests with the usage of polygons. In order to record and calculate the consequences of forest fires, it is necessary to have two pictures taken at different times: one before the fire, the other after (figure 6). In this way, we can ensure the accuracy, objectivity and reliability of the collected evidence. The necessary combination of channels for capturing the analyzed terrain can be obtained using the EO Browser cloud platform. The functionality of the platform allows us to measure the area of destroyed forests with the usage of polygons.

Table 3 shows examples of calculations of the territories of damaged forests of Kherson and Mykolaiv regions from shelling by Russian troops using this method. In general, during the period from February 24, 2022 to the moment of the occupation of the right-bank part of Kherson region, several thousand hectares of forest were destroyed only in the territory of these two regions. Detailed monitoring is necessary to obtain more accurate data.

The consequences of agricultural land fires are recorded using a similar method. As a result of Russian shelling in Ukraine, fires were recorded on almost 8,000 km^2 of agricultural land with crops of various farming cultures in just six months of the war. Documentation of the fact of fires is carried out in the presence of public reports from citizens, the government, local authorities, or based on the fixation of the source of ignition from satellite images of low spatial resolution (Terra MODIS). Then images of medium spatial resolution are obtained (Landsat 8, Sentinel 2A, 2B) and the area of the fire is determined in the short-wave infrared range (SWIR) (figure 7).

Table 4 shows examples of calculations of areas with crops in Zaporizhzhia and Kherson regions. It should be noted that forest and steppe fires destroy the fertile soil layer, and along

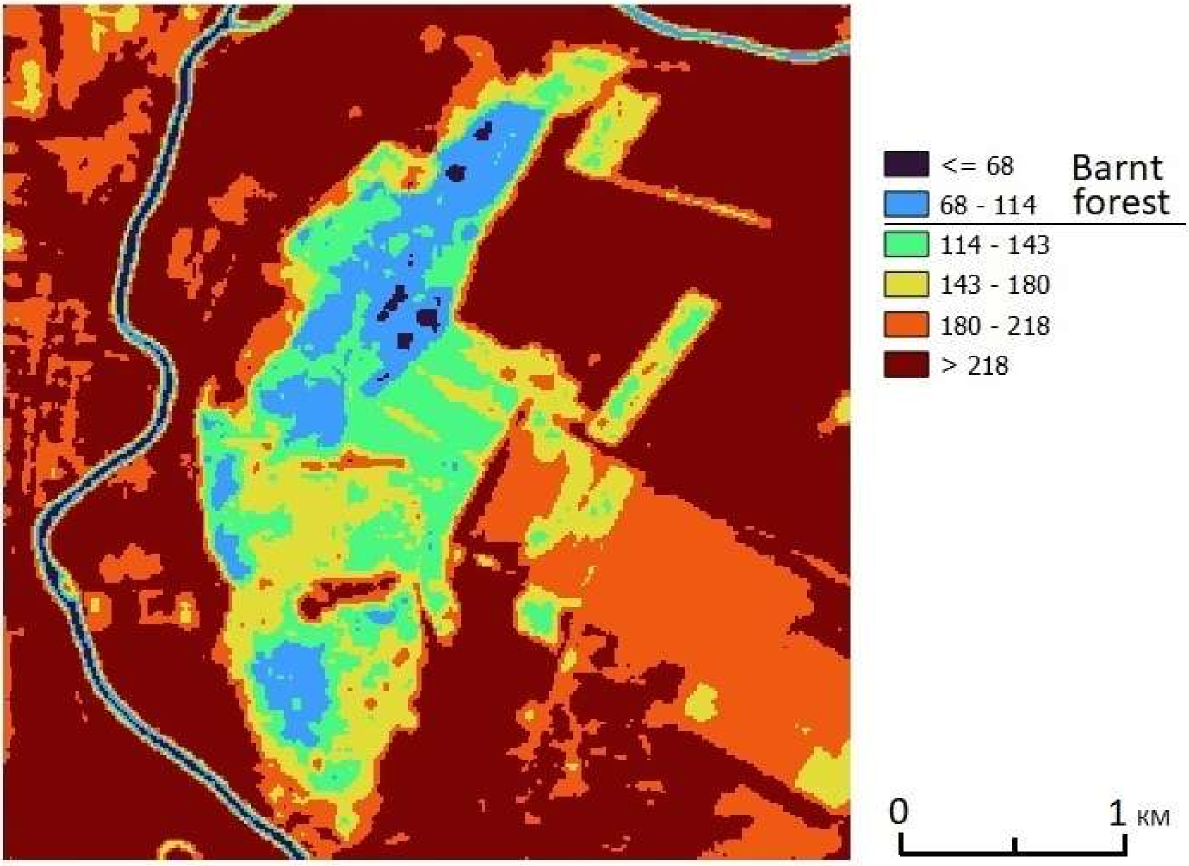

Figure 6. Raster classification of the satellite image of the Nedohirsky Forest in the QGIS program. The area of the burnt forest is marked by blue and black colours.

Table 3. Areas of forests damaged by military operations based on the analysis of satellite images [Satellite: Sentinel-2. SWIR range. Source: EO Browser].

№	Object name	Date of the picture	Burnt field area, km^2
1	Tyuryupynsk forestry (Kherson region)	22-07-15	0.25
2	Heroiske forestry (Kherson region)	22-07-23	0.7
3	Ivanivka forestry (Kherson region)	22-07-23	0.6
4	Nedohirsky forest (Kherson region)	22-05-31	0.4
5	Halytsynove Forestry (Mykolaiv region)	22-08-07	0.015

with it, millions of microorganisms that ensure the natural balance of the environment die. The number of animal and plant populations is also significantly decreasing. Determining the catastrophic consequences of these destructions and estimating the economic losses is possible only by conducting special studies on the area.

C. Destruction of structures (buildings) and constructions

One of the most significant indicators of the destructive actions of the Russian army in Ukraine is the destruction and damage of civilian and military infrastructure. According to official data from Ukrinform, during 300 days of the war, the occupiers destroyed at least 412 industrial

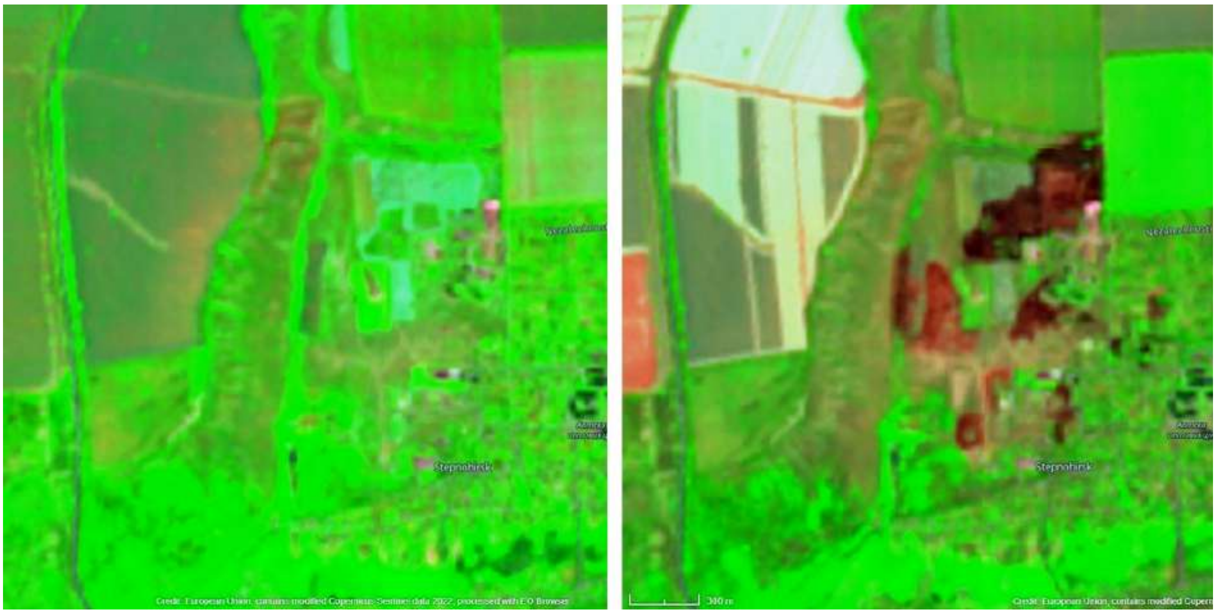

Figure 7. Satellite images of fields near the town of Stepnohirsk (Zaporizhia region). On the left – 22.06.20. On the right – 15.07.22. [Satellite: Sentinel-2. SWIR range. Source: EO Browser].

Table 4. Areas of agricultural crops damaged by fire from military operations according to the results of satellite image analysis [Satellite: Sentinel-2. SWIR range. Source EO Browser].

№	Object name	Date of the picture	Area of burnt crops, km^2
1	The town of Stepnohirsk (Zaporizhia region)	22-07-15	0.7
2	Novooleksiivka vil. (Genichesk district, Kherson region)	22-09-18	0.6
3	Novopokrovka vil. (Genichesk district, Kherson region)	22-09-18	0.5
4	Rozlyv vil. (Kherson Region)	22-08-24	0.12
5	Mala Tokmachka vil. (Zaporizhia region)	22-08-24	5.2

enterprises, more than 15,000 high-rise buildings, 116,000 private houses, almost a thousand medical facilities, 511 administrative buildings, etc. For each of these facts, it is necessary to form an evidentiary base, and considering the volume of work, the ERS becomes important.

To study the destruction of structures (buildings) and constructions, only satellite images with a very high spatial resolution (less than 1 meter – *GeoEye, WorldView-3*) are used. These pictures make it possible to compare the condition of buildings before and after the destruction (figure 8).

Due to the deciphering of the pictures, it is possible to assess the state of destruction of buildings. At the same time, it should be borne in mind that the analysis of satellite images, even with a very high spatial resolution, guarantees the diagnosis of the state of the building in three degrees of destruction: *completely destroyed, partially destroyed or not destroyed.* As an evidence base, such gradation may not be enough. In this case, the obtained data must be supplemented with additional information from verified sources (for example, an examination at the site of destruction), or using images from unmanned aerial vehicles

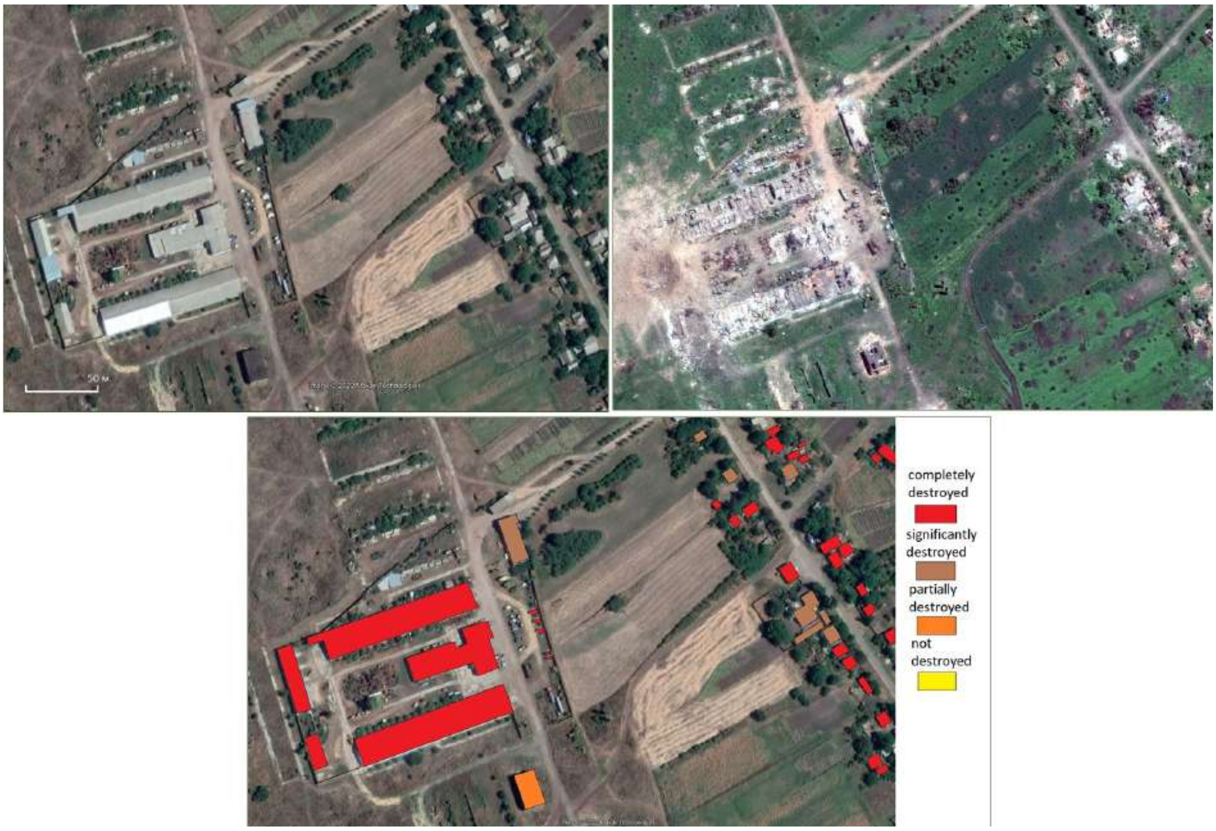

Figure 8. Visualization of buildings damage in the village of Dovgenkove (Kharkiv region) from shelling by Russian troops according to satellite images. Top left – 20.08.22, top right – 22.08.15. The picture below has been processed in the QGIS program [Source: Satellite Image 2022 Maxar Technologies, EPA].

So, for example, the companies SmartFarming and Vkursi Zemli launched the RebuildUA project, the purpose of which is to analyze and document the destruction of the infrastructure of populated areas as a result of Russia's war against Ukraine with the help of drones. The use of drones allows to collect more detailed data about the destruction: to take photos and videos of objects from different angles, from all sides of buildings.

In future, in order to ensure storage, quick search, analysis and visualization of all useful information, it is necessary to digitize it in the GIS environment. With the help of the GIS functionality on the raster image of the satellite photo, destroyed objects are recognized, their types are classified and the level of destruction is determined. Then these objects are digitized, with the creation of separate vector layers with appropriate consideration of their types and level of destruction (figure 8). In this form, the information is analyzed and stored.

Taking into account the amount of destruction in Ukraine, it is clear that recording and assessing the nature of damage as an evidence base requires a significant amount of work with the involvement of state and commercial organizations with experience in the field of practical application of ERS data.

4. Conclusions

1. Aerial photographs are a unique form of evidence of military destruction. The information obtained with their help reflects the general current and operational situation in the

destruction zone, reducing the subjectivity and uncertainty of damage characteristics on the ground.

2. Sources of satellite images are official state or commercial structures which are publicly available. This ensures the independence and persuasiveness of the obtained evidence for trials and lawsuits against the aggressor country.
3. Deciphering the data of remote sensing of the Earth makes it possible to obtain an accurate and complete assessment of environmental damage due to military actions according to the following indicators: degradation of land resources, destruction of natural ecosystems by fires, and destruction of structures (buildings) and constructions.
4. The proposed methodology for assessing military destruction is characterized by simplicity, accuracy and versatility, and does not require the use of expensive equipment.
5. It is possible to increase the effectiveness and evidentiality of the conclusions obtained from the analysis of the ERS data by applying additional surveys at the site of destruction.

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References

[1] Hettling J K 2003 *Space Policy* (19) 33–39 URL `https://doi.org/10.1016/s0265-9646(02)00063-2`
[2] Hoffmann C, Márquez J R G and Krueger T 2018 *Land Use Policy* **77** 379–391 URL `https://doi.org/10.1016/j.landusepol.2018.04.043`
[3] Witmer F D W 2015 *International Journal of Remote Sensing* **36**(9) 2326–2352 URL `https://doi.org/10.1080/01431161.2015.1035412`
[4] Levin N, Ali S and Crandall D 2018 *Applied Geography* **94** 1–17 URL `https://doi.org/10.1016/j.apgeog.2018.03.001`
[5] Sawalhah M N, Al-Kofahi S D, Othman Y A and Cibils A F 2018 *Journal of Arid Environments* **157** 97–102 URL `https://doi.org/10.1016/j.jaridenv.2018.07.003`
[6] Avtar R, Kouser A, Kumar A, Singh D, Misra P, Gupta A, Yunus A P, Kumar P, Johnson B A, Dasgupta R, Sahu N and Rimba A B 2021 *Remote Sensing* **13**(3) 439 URL `https://doi.org/10.3390/rs13030439`
[7] Ordway E M 2015 *Global Ecology and Conservation* **3** 448–460 URL `https://doi.org/10.1016/j.gecco.2015.01.013`
[8] Shatnawi N, Weidner U and Hinz S 2020 *Journal of Urban Planning and Development* **146**(3) URL `https://doi.org/10.1061/(asce)up.1943-5444.0000584`
[9] The World Bank 2017 The toll of war: The economic and social consequences of the conflict in Syria URL `https://openknowledge.worldbank.org/server/api/core/bitstreams/5001019f-4b12-5f67-b40f-f8ac12fd8a0e/content`
[10] Kahraman F, Imamoglu M and Ates H F 2016 Battle Damage Assessment based on self-similarity and contextual modeling of buildings in dense urban areas *2016 IEEE International Geoscience and Remote Sensing Symposium (IGARSS)* (IEEE) URL `https://doi.org/10.1109/igarss.2016.7730345`
[11] Kaplan G, Rashid T, Gasparovic M, Pietrelli A and Ferrara V 2022 *Land Degradation & Development* **33**(10) 1513–1526 URL `https://doi.org/10.1002/ldr.4249`
[12] Mueller H, Groeger A, Hersh J, Matranga A and Serrat J 2021 *Proceedings of the National Academy of Sciences* **118**(23) URL `https://doi.org/10.1073/pnas.2025400118`
[13] Zhao F, Bao J and Ming D 2020 Battle Damage Assessment for Building based on Multi-feature *2020 IEEE 5th Information Technology and Mechatronics Engineering Conference (ITOEC)* pp 57–60
[14] Garzón F A M and Valánszki I 2020 *Journal of Environmental Geography* **13**(3-4) 1–14 URL `https://doi.org/10.2478/jengeo-2020-0007`
[15] Melnyk N (ed) 2019 *Armed conflict in the east of Ukraine: damage caused to civilian housing* (Kharkiv: Human Rights Publisher)
[16] Derevyanchuk A Y and Shelest M B 2010 *Artillery weapons and ammunition* (Sumy State University)
[17] 2015 *Military actions in the east of Ukraine – civilizational challenges to humanity* (Lviv: EPL)

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Characteristics of BlaBlaCar as one of the world's ridesharing leaders

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Characteristics of BlaBlaCar as one of the world's ridesharing leaders

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Abstract. The article addresses one of the relevant global trends – the sharing economy or participation economy. The authors explore its features and benefits (time and resources saving, rational consumption, use of communication technologies etc.). The publication considers the driving forces, namely peering social networks, real-time technologies, the global economic crisis, environmental issues and a renewed belief in the importance of communities. The authors argue that BlaBlaCar is one of the world leading online ridesharing platforms. The article defines the essence of BlaBlaCar as a new model of shared consumption tracing the history of its inception and development. The authors examine characteristics and peculiarities of BlaBlaCar in terms of a modern information network; reveal the behavioral traits of BlaBlaCar users worldwide and in Ukraine. The article attempts to anticipate the prospects of BlaBlaCar development.

1. Introduction

1.1. The problem statement

Information plays a pivotal role in all spheres of post-industrial society. It is common knowledge that "whoever owns the information owns the world", as it is even more relevant today than in the days of Nathan Rothschild. The swift breakthrough of information technologies and the advance of information production brought about the growing economic importance of the information sector and the advent of new infrastructural elements – information networks. These networks contribute to the evolution of the sharing economy, since people exchange goods and services via them, so the transport is no exception.

The growing demand for transportation causes the creation of new information platforms offering transport services. To function properly transport service platform improve existing logistics systems and introduce a new transport trend – the joint trips in private vehicles arranged via online services for finding fellow travelers now known as ridesharing or carpooling. The term "ridesharing" is coined from two English words "ride" and "sharing" which mean to share a trip, and denotes the phenomenon when a driver or a passenger search for a companion to share a ride in order to travel costs. Carpooling is a shared car trip, agreed upon in advance between a car owner and passengers to save on fuel costs and to reduce the amount of traffic. Unlike hitchhiking, with carpooling, the costs of the trip are shared between the car owner and the passengers. Carpooling used to be practiced only by neighbors and acquaintances, currently with the advent of the Internet and social networks, this phenomenon reached a completely new level.

So, nowadays traditional car transport services are gradually being replaced by car sharing services, which by nature are an example of responsible consumption of resources.

Responsible consumption and production [1, 2], is correspondently the twelfth goal of sustainable development proclaimed by the UN General Assembly in 2015. One of the feasible ways to accomplish this objective is to develop information transport networks, e.g. BlaBlaCar [3], since their advantages in the environment protection are absolutely apparent, because car sharing is incomparable means in reducing humanity's carbon footprint.

The transition to a shared consumption economy is a modern key to sustainable development, which meets the needs of the current generation without threatening the following generations to meet their own needs [4].

1.2. The objective of the article

Within the scope of this publication, we aim to examine the characteristics of BlaBlaCar as one of the world ride-sharing leaders, to consider its advantages and disadvantages, to envision the prospects for its development.

1.3. Theoretical background

There is a growing body of literature that recognizes the importance of the sharing economy, among which are the studies of Lessig [5], Deakin et al [6]. We want to acknowledge the works of Botsman and Rogers [7], Walsh [8], Mazzella [9], Sundararajan [10] on the advantages and pitfalls of the participation economy. Jiang and Tian [11], Barbu et al [12] recognises the critical role played by responsible consumption in the sustainable development. Kim and Jin [13], Mukhopadhyay and Mukhopadhyay [14], Luri Minami et al [15] address the relevant issue of information transport networks. In Ukraine, the phenomenon of sharing is still relatively new and is just beginning to spread [16–21].

However, the researches to date have not yet established how the sharing economy works. Much uncertainty still exists about the advantages of ridesharing compared to traditional transportation services. It is now well determined whether people are ready to share with each other and to what extend exactly. The influence of the quarantine restrictions caused by the global pandemic or the war in Ukraine on carpooling has remained unclear. A number of questions concerning the prospects for the development of information networks are particularly relevant.

The research data in this publication is drawn from three main sources: reports and statistical materials of various companies and their branches, publications and information resources that are freely available and are relevant to the problem of ridesharing or carpooling. As we consider the BlaBlaCar information network as an example of a sharing platform, so data for this study were collected from its official website.

2. Results and discussion

The digitization of modern society encouraged by rapid development of information technologies has led to the emergence of the sharing economy making it a trend modern world. The basis of the sharing economy is the sharing of goods or services, not their ownership. Therefore, it is not the ownership of goods or services that is important nowadays, but timely access to them. Hyper consumption, widespread in the 20th century, was replaced by joint consumption, characteristic of the 21st century [6]. Thus, a new responsible model of consumption and a new approach to any resources use are gradually refined. These models are definitely more appropriate for present-day, as they contribute to the sustainable development of mankind.

Rachel Botsman, a well-known propagandist of the sharing economy, convincing responded a question why humanity should move to a more coherent and responsible consumer culture [22]. In her speech at the TED conference back in 2010, she noted that the majority of people owning a drill use it for only 12-13 minutes of the entire operation time. A car, of about $8,000 average cost, is usually idle for 23 hours a day. Botsman introduced the idea of sharing the equipment or tool by borrowing, lending or leasing them. This constitutes the primary idea of shared consumption economy – instead of possessing, people can share resources, which makes more efficient use of material goods and reduces the costs of their acquisition or production.

Fred Mazzella, a founder of BlaBlaCar, characterized the era of sharing and emphasized that humanity "stands on the threshold of the era of exchange" of goods, knowledge, money, time, skills, content, etc. "The arrival of the sharing age is a logical evolution from the disruptive innovations of the early 2000s, all of which are now allowing individuals to scale their network and gain access to solutions best suited to their needs. But the phenomenal growth and continued popular support of these models is better explained by the virtuous impacts of sharing" [8].

Botsman and Rogers [7] investigate the positive impact of the sharing of goods and services in their research. Moreover, their book *What's Mine Is Yours: Rise of Collaborative Consumption*, substantiates the basic principles and driving forces of the sharing economy [6]. Let us briefly characterize them using the example of ridesharing.

Internet sharing platforms exist all over the world, but they are predominantly developed in European countries such as Belgium, Great Britain, Italy, Spain, the Netherlands, Germany, Poland, France and Sweden. The number of sharing companies and their incomes grow annually, which indicates the growing demand in them among the world's population [2].

Carpooling came into being in the USA and the countries of Western Europe in the 40s of the XX century, and with the advent of the Internet, it received an impetus for development. According to Mordor Intelligence [23], the ride-sharing market will continue to grow rapidly due to the increasing demand for economical and timesaving vehicles and by 2027 it will grow by 18%. The European region presently demonstrates the largest carpooling market, although the Asia-Pacific region shows the signs of even faster growth.

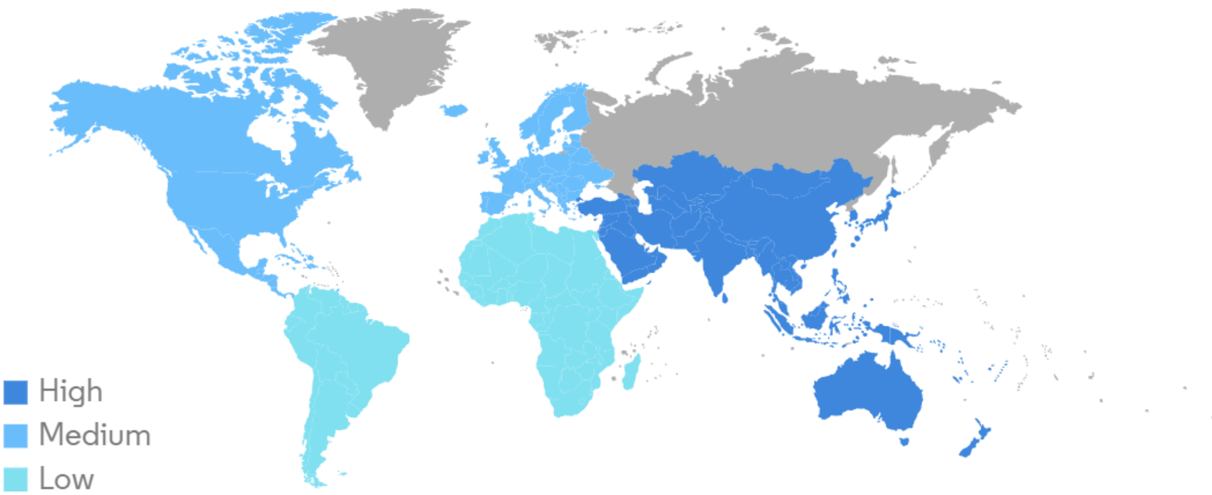

Figure 1. Global Ridesharing Market – Growth Rate by Region (2022 – 2027) [23].

Being the booming market, ridesharing constantly attracts new market players offering transportation services. It is worth mentioning such major players as Via Transportation, Scoop Technologies, Mahindra Logistics Ltd. UCR, Didi Chuxing Technology Co, Zimride, Uber, Nuride, Zipcar, Turo, Getaround, Rides Ridingo, and JayRide.

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Table 1. Basic principles and driving forces of the sharing economy on the example of ridesharing.

Sharing Economy	Ridesharing
Basic principles of functioning and their characteristics	
Profit. In case of use, it brings benefit, in case of idling, it causes lost	Renting a car reduces maintenance costs. Carpooling reduces transportation costs for trip participants. The car owner saves money and resources, fuel, parking fees, maintenance of the vehicle and guarantees to fellow travelers that they will arrive at their destination on time
Saving time and resources (to use, it is not necessarily to own)	Renting a car for a small fee is more profitable than buying it, as modern young people are not usually tied to the place of their residence or work
Rational consumption	Minimizing traffic should effect total fuel consumption, and correspondingly the decrease in harmful emissions and the carbon footprint in the atmosphere
Trust as a basis for sharing	The growth of the carpooling market contributes to an increase in the general level of trust in society
Use of communication technologies	Information platforms providing car transport services contribute to the connection between the car owner and potential passengers
Driving forces of sharing	
Peering social networks and real-time technologies	The quality of communication improves because peering social networks establish a powerful sharing connection between the physical and virtual spheres of life. The economy of shared consumption and its platforms have become the most convenient and cheap means of client information compared to the traditional ones [19]. All mentioned above leads to a reduction in traffic and efficient use of motor vehicles.
World economic crisis	It caused the refusal of people from mindless consumption in favor of responsible consumption; the use of resources and goods, cars particularly, in order to ensure sustainable social development
Environmental issues	The aggravation of environmental issues made the humanity change the approach to their solution from an anthropocentric to an eco-centric. Ridesharing is considered to be one of the means to reduce anthropogenic impact on nature, especially on the atmosphere
Growing trust between people	The basis of ridesharing is the concept of “trust” (client – driver, driver – client).

BlaBlaCar is considered one of the leaders in the shared ride market, and can serve as a vivid example of the sharing economy. BlaBlaCar is a carpooling information network that provides drivers with the opportunity to save on gas expenses and travelers to economize on fares due to shared cost of trip, which turns out to be lower, compared to rail and airline fares. According to the BlaBlaCar regulations, drivers compensate most of the fuel costs allowing passengers to travel cheaper than in public transport.

BlaBlaCar presently supports the intersection of more than 100 million drivers and passengers who share the common goal of traveling cheaply and conveniently. BlaBlaCar as a leader in its field to date offers a variety of route options especially for short distances (less than 150 km).

BlaBlaCar is not only an online platform for a more effective search of traveling companions, but also a cloud data storage. The company has an Internet service that monitors possible trips, warns against fraud and organizes correspondence or calls between a driver and passengers. The international web site of this service is currently functioning in 22 countries worldwide.

We can distinguish three stages of the BlaBlaCar development presented in table 2.

BlaBlaCar is also a powerful information network that takes into account the needs of every person, regardless of age and gender. The information found in the BlaBlaCar network can be grouped into the following categories: rules of use, user characteristics, social impact, environmental efficiency and regional features of user behavior. BlaBlaCar has clear terms of use that allow everyone convenient and safe travel experience:

- registration and profile filling;
- submission of an application to search for fellow travelers or a vehicle.

Registration and profile filling phase suggests different ways of registration possible (via a Facebook account, via e-mail) and entering minimal user information (name, gender and year of birth, preferences, photo). Car owners also need to specify the technical characteristics of their vehicle.

On the phase of submitting an application for travelling companion or finding a car, users can fill out a special form with the place of departure and destination, date and time. After the ride, passengers and drivers leave feedback about the shared ride, which affects trust in the community. There are several criteria for choosing a travel partner or a vehicle, including comfort, price, route, time of a trip, age and experience of the driver and reviews on BlaBlaCar. At the same time, the service is available via mobile applications for iPhone and Android, as well as on the main website on the Internet.

The findings merged from the data analysis can identify the following generalized characteristics of BlaBlaCar users:

- the majority (about 2/3) of BlaBlaCar users are males (62%). We believe that the main reason for the smaller number of female users is the issue of safety, less trust of women in unfamiliar drivers and passengers. To ensure women feel comfortable and safe, BlaBlaCar provides the "Girls Only" option;
- the diversity in age with the predomination (more 1/2 making 43%) of young users (aged 25 to 34), people aged 35 make up 30% of users. This can be explained by the fact that this age group are the most advanced users of social networks, the main consumers of goods and services of the sharing economy;
- BlaBlaCar enables people with special needs to use network services by changing interface settings, zoom and navigation using the keyboard.

We believe an important feature of BlaBlaCar is the positive environment effect due to the reduction of traffic. The report of the French research institute *Le BIPE BRO* [24] on the results of a study, commissioned by the BlaBlaCar company, states that in 2018 BlaBlaCar users, traveling with fellow travelers and sharing fuel costs, reduced CO_2 emissions by approximately 1.6 million tons. The projected saving of CO_2 emissions (in millions of tons) as of 2023 is presented in figure 2. According to the 2018 IPCC report, stabilizing global warming at 1.5°C requires reducing CO_2 emissions by 45% no later than 2030.

Therefore, ridesharing trend and BlaBlaCar particularly can make a huge difference in solving a number of issues and may contribute to the sustainable development of humanity in the near future.

Table 2. Development stages of BlaBlaCar.

Development stages	Stage characteristics
1. The emergence of BlaBlaCar (2006–2010)	The idea to create BlaBlaCar dates back 2004 and belongs to Fred Mazelli, who wanted to go to visit his relatives outside the city, but could not get to them. It occurred to Fred to find a driver who was willing to take him as a passenger on the condition that he shared fuel costs. That shared trip inspired Fred Mazelli to create an information site for finding fellow travelers, and in 2006 Fred Mazzelli purchased the *covoiturage.fr* domain. The co-founders of the project were Fred Nappeson, Nicolas Brusson and Olivier Bonnet. At this stage, the product development strategy was worked out and planned.
2. Development of BlaBlaCar and its entry into the European market of shared trips (2011–2014)	BlaBlaCar enters the European market using different websites (for example, in Spain, the company is called Comuto with the website *comuto.es*). In June 2011, the company expanded its services to the UK and changed the name to BlaBlaCar, as users indicated their level of “talkativeness” from “Bla” (silent), “BlaBla” (moderately talkative) to “BlaBlaBla” (very talkative) when registering on the site. In 2012, BlaBlaCar entered the market of 6 more European countries: Belgium, Italy, Luxembourg, the Netherlands, Poland and Portugal. The Spanish and French sites were renamed to standardize the network. At this stage BlaBlaCar became one of the most expensive startups in Europe thanks to the investments of Insight Venture Partners and Lead Edge Capital.
3. New markets extension, new product offers (2014–2023)	BlaBlaCar came to Turkey in 2014, and India the following year. 2015 was the year BlaBlaCar expanded into Latin America, particularly Mexico and Brazil, with $200 million funding. Since 2019, BlaBlaCar has become part of the BlaBlaCarPro international project, which is a legal bus carrier service. It assists carriers and bus fleet owners to find passengers for nearly 100 million BlaBlaCar users. However, only carriers with legal license to transport passengers can work with this service. In 2018, BlaBlaCar moved beyond carpooling for the first time, announcing the purchase of Ouibus, one of France’s largest bus operators, owned by the state-owned SNCF, which manages the country’s railways. Later on BlaBlaCar, the world’s largest carpooling service for long-distance trips, announces a joint effort with Busfor, the leading service for finding and buying bus tickets in Ukraine and other countries of Central and Eastern Europe. The merger of companies was supposed to contribute to the expansion of BlaBlaCar in the passenger transport market in the region with a population of more than 300 million people. With the onset of the global COVID-19 pandemic, demand for transportation services and platforms dramatically increased as public transportation and intercity transportation were shut down. In this regard, since April 2020, BlaBlaCar has launched a new *BlaBlaHelp app.*, the application helps buy products or medicines in a pharmacy.

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Figure 2. Projected savings of CO_2 emissions [24].

The next stage of our research aims to reveal the behavioral traits of BlaBlaCar users in various regions worldwide. The results of this study show that the behavior of BlaBlaCar users in different countries demonstrate no fundamental divergence. However, it has been established that users from different regions still have some distinctions due to peculiarity of mentality and cultural customs.

The most interesting finding concerns the time and details of the trip planning. For example, the users from the Western, Southern and Northern European countries usually plan shared trip a week or two in advance, and clarify the trip details and check the driver's profile in 2-3 days before the trip takes place. The Central and Eastern Europe users also plan a trip, but usually in 2-3 days, and they clarify the trip details on the day of departure. Moreover, they rarely carry out a detailed check of the driver's profile. However, users from Latin American countries may plan a trip a week in advance, but can often cancel it in 2-3 days; also the driver profile check may not be very detailed.

In the countries of the Asian region, users strictly observe customs and traditions peculiar to oriental culture. Thus, women in India, for example, ride only with a female driver. The gender of the user determines the thoroughness of detail checking in the driver's profile.

BlaBlaCar entered the Ukrainian market in February 2014 due to the takeover of *Podorozhniki*, the Ukrainian startup, whose founder and first regional manager was Oleksiy Lazorenko. In January 2022, because of personnel changes Roman Miroshnichenko took the position of general director of BlaBlaCar in Ukraine.

As of 2023, Ukraine is among the top three countries where BlaBlaCar is developing rapidly. The Ukrainian BlaBlaCar market has currently 8 million users, of which 1 million people use it every month. About one hundred employees work in the Ukrainian office of the company. The analysis of the data taken from the company's official website reveals that 55% of users use the network for vacation trips, 49% for visiting parents or relatives, and 42% for business trips.

Passenger traffic traditionally increases on the eve of holidays. The most popular in 2019 (in terms of the number of seats offered in the cars) proved to be summer destinations in Ukraine, i.e. see resort cities: Berdyansk (Zaporizhia region); Kyrylivka (Zaporizhia region); Iron port (Kherson region); Zatoka (Odesa region); South (Odesa region). Among the most popular winter resort regions were: Bukovel (Ivano-Frankivsk region); Vorokhta (Ivano-Frankivsk Region); Yaremche (Ivano-Frankivsk Region); and Skhidnytsia (Lviv region).

Unfortunately, with the full-scale invasion of Russia into Ukraine, the former popular summer travel destinations are no longer relevant.

The introduction of quarantine restrictions caused by the COVID-2019 pandemic, followed by the Russian-Ukrainian war, effected the development of BlaBlaCar in Ukraine.

In March 2020, BlaBlaCar appealed to its users asking to stop traveling temporarily and urged to use the platform only for exceptional and urgent trips. In accordance with the Government of Ukraine decision to ban passenger transportation, dated March 16, 2020, BlaBlaCar temporarily suspended all bus trips, including on the Busfor platform.

Presently, the government of Ukraine gradually allows restoring long-distance travelling. BlaBlaCar introduced improvements and new features on the platform that are called to assist traveler's necessary safety measures and health precautions. BlaBlaCar reminds every user of safety recommendations the moment he/she post or book a ride, including: not to drive in case of COVID symptoms arise, to wear a medical mask, to keep a safe distance, and not to hold hands.

In April 2020, BlaBlaCar announced the launch of *BlaBlaHelp (iOS, Android)*, a free application that helps buy essentials during the spread of COVID-19 [25]. To date, more than 35,000 users apply *BlaBlaHelp* and the company encourages its users to share the application with those who may need help.

One more company's initiative is the assistance to the Armed Forces of Ukraine by making quick and free of charge trips for the militaries who need to get to their destination.

In the conclusion, we can summarize the salient features of the BlaBlaCar information network:

- BlaBlaCar information network is a part of the sharing economy, which is developing at a fast pace;
- the network provides users with wide possibilities to make trips;
- BlaBlaCar interacts and cooperates with other sharing platforms, expands the car sharing service on the world market;
- the network differs from traditional types of logistics systems;
- some aspects of BlaBlaCar activities are partly non-commercial, international, global and informal;
- BlaBlaCar provides cross-cultural exchange through communication opportunities between users;
- users can travel in any direction and at any time;
- BlaBlaCar site is accessible for users with special needs.

Considering the features listed above, we can distinguish the main advantages and disadvantages of BlaBlaCar.

The main advantages of BlaBlaCar over its competitors, i.e. transport companies, are: a slightly lower price of the trip; free choice of more favorable route and time; individually suitable location of departure and destination; the availability of trip routes that are not provided by the regular carriers; less emission of CO_2 into the atmosphere; and mutual assistance during the COVID-19 pandemic.

We see the main disadvantages of BlaBlaCar as follows:

- many drivers use the BlaBlaCar platform for commercial purposes, although it is against the terms of use of the free platform;
- the lack of reporting documentation, which can create problems with taxation and insurance;
- the issue of income accounting and taxation: the lack of real mechanisms for monitoring the flow of money which causes the transfer of part of the money into the "shadow";

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- insufficient safety guarantee for passengers and drivers;
- in most countries, BlaBlaCar works only with long-distance transportation, which limits the capabilities of the platform;
- passengers have to tolerate the time and route offered by drivers, which may not always meet their needs;
- the transition from a social platform to a business platform may lead to an increase in service prices and change BlaBlaCar's philosophy.

3. Conclusion

Sharing economy in general and ridesharing in particular grounds in financial benefit, time and resources saving, rational consumption, trust, and communication technologies. Nowadays BlaBlaCar is a new model and a vivid example of the economy of shared and responsible consumption. It is one of the world leading online sharing platforms, which has gone a long path from the idea of finding fellow travelers to mastering the global market of shared trips and offering new products (bus trips, BlaBlaHelp, etc.).

BlaBlaCar has as advantages (traffic minimization, lower trip price, free route and time choice, CO_2 emission reduction), as some disadvantages (insufficient guarantee of passenger and driver safety, lack of reporting documentation, restrictions on intercity transportation).

Thus, BlaBlaCar is a special information network with unique characteristics that distinguish it from other similar networks, and some common features with existing sharing platforms, such as the user communication available. BlaBlaCar is an innovative solution in passenger transportation issue, which has gone through successful testing on the world market and proved competitive with the other companies.

As the prospects of BlaBlaCar development, we can envision the entry of insurance companies into the BlaBlaCar market and implementation of monetization; expansion of the service market and entry to the joint transportation market of Japan, South Korea, Indonesia, Colombia, and Argentina, etc.

Our further scientific research aims at the study of modern trends in the development of the sharing economy in the global economic system.

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References

[1] United Nations 2015 Transforming our world: the 2030 Agenda for Sustainable Development URL https://sdgs.un.org/2030agenda
[2] PwC 2016 Making a difference: Global Annual Review 2016 URL https://www.pwc.com/gr/en/about-us/assets/pwc-global-annual-review-2016-making-a-difference.pdf
[3] BlaBlaCar URL https://www.blablacar.com/
[4] United Nations 2022 The Sustainable Development Goals Report 2022 URL https://unstats.un.org/sdgs/report/2022/The-Sustainable-Development-Goals-Report-2022.pdf
[5] Lessig L 2008 *Remix: Making Art and Commerce Thrive in the Hybrid Economy* (New York: Penguin Press) URL https://textbookequity.org/Textbooks/Remix.pdf
[6] Deakin E, Frick K T and Shively K 2012 *ACCESS Magazine* (40) 23–28 URL https://escholarship.org/uc/item/1c0421x7
[7] Botsman R and Rogers R 2010 *What's Mine Is Yours: The Rise of Collaborative Consumption* (HarperCollins Publishers)

[8] Walsh B 2011 Today's Smart Choice: Don't Own. Share URL http://content.time.com/time/specials/packages/article/0,28804,2059521_2059717_2059710,00.html
[9] Mazzella F 2016 The Sharing Age URL https://techcrunch.com/2016/02/04/the-sharing-age/
[10] Sundararajan A 2017 *The Sharing Economy: The End of Employment and the Rise of Crowd-Based Capitalism* (Cambridge, Massachusetts: MIT Press)
[11] Jiang B and Tian L 2018 *Management Science* **64**(3) 1171–1188 URL https://doi.org/10.1287/mnsc.2016.2647
[12] Barbu C M, Florea D L, Ogarcă R F and Barbu M C R 2018 *Amfiteatru Economic* **20**(48) 373–387 URL https://doi.org/10.24818/EA/2018/48/373
[13] Kim N and Jin B E 2018 *International Textile and Apparel Association Annual Conference Proceedings* **75**(1) URL https://www.iastatedigitalpress.com/itaa/article/id/1451/
[14] Mukhopadhyay B R and Mukhopadhyay B K 2021 *The Sentinel* URL https://www.researchgate.net/publication/351122120
[15] Luri Minami A, Ramos C and Bruscato Bortoluzzo A 2021 *Journal of Business Research* **128** 124–137 ISSN 0148-2963 URL https://doi.org/10.1016/j.jbusres.2021.01.035
[16] Kuksa V 2018 *Finansovyi prostir* (2 (30)) 71–79 URL http://nbuv.gov.ua/UJRN/Fin_pr_2018_2_9
[17] Yakovleva M 2019 Podilytysia zi svitom: shcho daie ukraintsiam sherinhova ekonomika [Sharing with the world: what the sharing economy gives Ukrainians] URL https://tyzhden.ua/Economics/229889
[18] Parsenyuk V and Pashchenko O 2020 *Young Scientist* (11 (87)) 186–192 URL https://doi.org/10.32839/2304-5809/2020-11-87-40
[19] Kraus N, Kraus K and Osetskyi V 2021 *Efektyvna ekonomika* **4** URL https://doi.org/10.32702/2307-2105-2021.4.3
[20] Kraus K, Kraus N and Holubka S 2021 *Efektyvna ekonomika* URL https://doi.org/10.32702/2307-2105-2021.8.73
[21] Sotnyk I M and Dolhosheieva O I 2021 Sherinhova ekonomika yak skladova staloho rozvytku [Sharing economy as a component of sustainable development] *Ukraina u svitovykh hlobalizatsiinykh protsesakh: kultura, ekonomika, suspilstvo : tezy dopovidei Mizhnarodnoi naukovo-praktychnoi konferentsii, m. Kyiv, 24–25 bereznia 2021 r.* vol 3 (Kyiv: Vyd. tsentr KNUKiM) pp 133–136 URL https://essuir.sumdu.edu.ua/handle/123456789/83560
[22] Botsman R 2010 Collaborative Consumption Author Presents Compelling Case for 21C URL https://www.youtube.com/watch?v=zpv6aGTcCl8
[23] 2023 Ridesharing Market Size & Share Analysis – Growth Trends & Forecasts (2023 - 2028) URL https://www.mordorintelligence.com/industry-reports/ridesharing-market
[24] BlaBlaCar 2019 Zero Empty Seats: A study into BlaBlaCar's environmental contribution URL https://www.clasicosalvolante.com/wp-content/uploads/2019/03/EN_Environmental_Report.pdf
[25] 2020 BlaBlaCar launches BlaBlaHelp URL https://blog.blablacar.com/newsroom/news-list/blablacar-launches-blablahelp

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The problem of rational use of mineral resources and mining waste in the context of sustainable development of regions

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Abstract. Efficient use and protection of the subsoil is a part of rational nature management in the mineral base of Ukrainian regions and Ukraine as a whole. The components for the rational use of the subsoil include a comprehensive development of mineral deposits, a comprehensive use of mineral raw materials and mining waste, optimization of the structure of mining production and mineral raw materials consumption. The rational use of mineral resources in the modern interpretation of this issue extends to all stages of their development, including the issue of waste disposal. A huge amount of mining waste has been accumulated in administrative regions of Ukraine, and the issue of their disposal has gone beyond just an economic and ecological problem and has acquired a significant socio-demographic significance. Environmental problems have become particularly acute due to the accumulation of toxic waste, among which the most dangerous are heavy metals, petroleum products and acid tars. For the sustainable development of Ukraine, it is necessary not only to develop new reserves of natural raw materials, but also technogenic minerals accumulated in more than 1,600 man-made deposits and objects. The further development of the mineral base requires, at the state level, an urgent solution to problems that hinder the development and ecological rehabilitation on the ground of rational use.

1. Introduction

Hundreds of billions of tons of various types of mineral raw materials: combustible minerals, ores, construction materials, etc., are mined from the subsoil every year. Along the way, in the process of mining, host rocks are also removed and remain at the mining site. Human activity has acquired global dimensions and is commensurate with the geological processes involved in the formation of the planet's landscapes. Long-term exploitation of mineral resources has led to the reduction of their reserves and the depletion of rich or unique deposits. At the same time, the non-restoration and limited reserves are characteristic of the mineral resources, so it is important to find approaches to the effective use of their reserves in order to prevent depletion and excessive losses during extraction. The growing technogenic load and disturbance of the natural environment during the exploration and exploitation of mineral deposits make the issue of overall protection of the geological environment and landscapes an urgent one.

The geoecological approach of the mineral resources study arose mainly on the ground of a need to study the processes accompanying the exploration, extraction and primary processing of minerals [1]. It is caused by the need to monitor, analyze and forecast, aimed at minimizing the negative impact of mining production on the environment, the development of rational schemes for the environmentally safe activities of mining enterprises in the context of optimizing in nature management. The result of the geoecological study of mining areas is the development of measures to improve the quality and conservation of the natural environment and reclamation of mining landscapes. The research is focused on the following issues: protection and rational use of subsoil, surface and groundwater, air environment, reclamation of lands disturbed by mining, disposal of mining waste, ecological and landscape problems of disturbed territories. Due to the global nature of the issue, the purpose of this article is to analyze only the first problem – the rational (efficient) use of mineral resources and mining waste.

The issue of conservation and rational use of subsoil resources has been of particular interest to researchers since the late 1960s and early 1970s, but the majority of publications fall into the 1980s. First and foremost, these are the works of Melnykov [2], Pedan and Mishchenko [3], Rekitar et al [4], and Bent [5]. Among the publications of the last decades, the works of Rudko and Shkitsa [6], Andrievsky [7], Galetsky et al [8], Komov [9], Panov [10], Rudenko et al [11], Mishchenko [12], Syvyi et al [1], Udalov and Kononenko [13], Kilinska and Kostashchuk [14], Rudko et al [15], Hrinov and Khorolskyi [16] should be mentioned. The mentioned works discuss methodological approaches to the rational use of mineral resources. In particular, they develop a conceptual framework, classifications of ways to comprehensively use mineral resources, the main directions of use, classifications of mining and industrial waste and problems of their disposal, the role of comprehensive use of mineral resources in improving the territorial organization of social production, the effectiveness of comprehensive development of mineral resources, and so on. The theoretical and methodological justification of these directions, the development of technological schemes for extracting valuable components at different stages of the mining production process, and finally, the globalization of the problem – i.e., the processing not only of the methodology of rational use of mineral resources, but also of the rational use and protection of subsoil resources in general – are some of the topics discussed in these and many other works that remain relevant today.

2. Results and discussion

Rational use and protection of the subsoil is an integral part of rational nature management within the mining areas. Rational nature management should be understood not merely as the optimization of the processes of intensive use of natural resources and their protection, but also as a system of measures covering the issues of environmental protection and control, reproduction and preservation of these resources, effective use of capital investments in mining enterprises, the distribution of the productive forces of the region [17].

From the general issue of rational nature management in the region, one can single out the rational use of mineral resources. Equally important components of the latter are comprehensive development of mineral deposits, comprehensive use of mineral raw materials and mining waste, optimization of the structure of mining production and mineral raw materials consumption (figure 1).

The maximum satisfaction of society's needs in certain types of raw materials at specified costs and under the condition of compliance with environmental standards can be considered as a criterion for the effective and optimal use of mineral resources. At the same time, factors of an economic, ecological and social nature should be taken into account; in particular, meeting needs for a certain resource, a level of current costs in the production and consumption of the product, economic effect and trends in the development and use of subsoil resources, the implementation of measures to preserve resources for future generations; minimization of harmful effects of

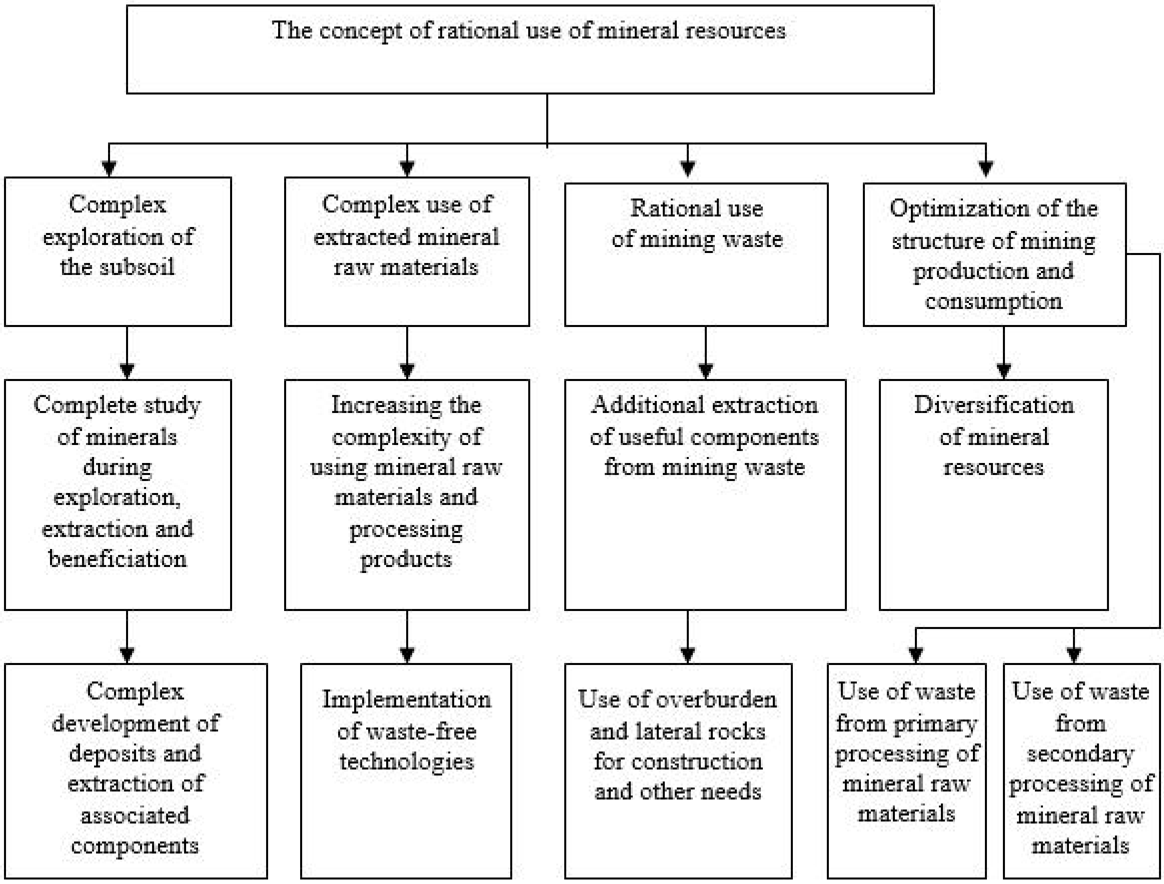

Figure 1. Structure of measures to solve the problem of rational use of mineral resources of the region.

mining on the environment, etc.

Irrational extraction and use of mineral raw materials lead to an increase in costs at all stages of mining production. Losses of minerals during their extraction and primary processing in some cases amount to 40-50%. The growth of mineral losses causes a deterioration in the quality or a decrease in the volume of concentrates produced by mining enterprises due to a decrease in the volume of useful components, a reduction in reserves due to their faster depletion. Mineral raw materials depletion of reserves is one of the main problems of environmental protection. High-waste technologies, non-comprehensive use of mineral raw materials and, as a result, environmental pollution, violation of its dynamic balance are other parts of this problem.

The list of tasks for rational use of mineral resources at various stages of their development and environmental protection issues, which need solving, has a following look (table 1). Rational use of mineral resources covers all stages in their development (search and exploration of deposits, extraction, transportation, primary and secondary processing), including waste disposal. The waste disposal is limited to those groups and types of waste processing, which are direct replacement of certain mineral resources.

The optimal use of mineral resources includes, on the one hand, the most detailed study of deposits at the stage of exploration, pre-exploration and exploitation, the choice of rational schemes for the most complete extraction of useful components during mining enrichment and processing; and, on the other hand, a requirement for a comprehensive use of mineral raw

Table 1. Tasks of rational use of mineral resources and environmental protection.

Stages of development of mineral resources	**Main tasks**		
	Study and complete extraction of mineral resources	**Complex use of mineral resources**	**Environment protection**
Search and exploration of mineral deposits	Rational and effective works on subsoil exploration; complete study of the geological structure; reliability of determination of reserves and quality of minerals; a rational approach to establishing the conditions of mineral raw materials	Research of associated components of raw materials and useful components in overburden, lateral and underlying rocks	Implementation of works without unjustified loss of minerals; prevention of pollution of water horizons; preservation of exploratory mines and wells and their liquidation, if they are not suitable for use and have environmental damage
Extraction of minerals	Selection of rational schemes for exploitation of deposits; reduction of losses in the subsoil; ensuring the maximum completeness of working out the reserves of the deposit	Organization of complex development of the deposit; preservation and accounting of associated components through their selective extraction and storage; utilization of overburden and host rocks	Preventing the negative impact of mining and other types of work on the preservation of mineral reserves; protection of deposits from flooding, pollution and construction; treatment of mine wastewater; air protection in quarries; prevention of oil leakage; rehabilitation of disturbed lands; protection of nature conservation objects
Transportation and processing of mineral resources	Complete extraction of useful (including associated) components from mineral raw materials; reduction of losses during transportation and processing	Economically expedient extraction of associated components from mineral raw materials; use of waste from primary and secondary mineral processing	Use of rational waste storage and preservation schemes with minimal loss of land; use of modern technologies to prevent pollution of the air environment, underground and surface waters, soils, etc

materials (t1). The methods and means of extracting minerals, which are used in modern technologies, do not solve the issue of their complete extraction from the subsoil. The resulting losses sometimes exceed the volume of actual production. Particularly significant losses are recorded in the underground method of development; a quarry method, as a rule, can reduce the loss of raw materials by 3-8%.

The problem of comprehensive use of mineral resources is considered in two aspects: a comprehensive development of deposits and a comprehensive use of raw materials.

A comprehensive development of deposits involves the use of rational, effective methods of extraction of the main and associated useful components in host and overburden rocks. Selective extraction of all industrially valuable components, their storage, and shipment to the consumer, or their accounting, in case of temporary non-use, must be ensured. Most mineral deposits are multiply. Sometimes the content of accompanying components can have a completely independent value, and their economic value may even exceed the cost of the main raw material. Multiple components are an important and permanent feature of mineral resources. Genetic associations of minerals (paragenesis) are well known in petrology, and the need for a comprehensive approach in solving the issues of using mineral raw materials is based on the following: the main component associates with a number of other components. Paragenesis is especially typical for ores of non-ferrous metals. During the comprehensive processing of ore raw materials, in addition to 8-12 profiling chemical elements, additional 62-66 elements can be obtained [15].

The economic effectiveness of the comprehensive use of mineral resources is revealed in various approaches. First of all, the accompanying extraction of valuable components significantly expands the mineral base. This is most important for non-ferrous metallurgy, where the majority of rare elements are contained in ores of basic metals. Sometimes there are much fewer of them in special deposits of rare metals. At the same time, in the process of mineral raw materials comprehensive use, conditions are created for increasing the volume of production with significantly lower capital costs. Many diffuse elements do not have their own minerals at all. Selenium, tellurium, indium, thallium and rhenium are extracted only from non-ferrous metal production waste, which is the only possibility of their production through complex processing of polycomponent ores. Most of the accompanying components are considered valuable, and even incomplete extraction of them from mineral raw materials makes it possible to expand the raw material base of the industry, reduce production waste, increase its economic efficiency and improve the environmental situation.

In addition to the extraction of industrially valuable components from raw materials, its comprehensive use requires the disposal of host and overburden rocks and residual products of enrichment and processing of raw materials. Up to 0.5-0.6 billion tons of rocks and mineral raw materials processing waste are stored annually in surface dumps. The total amount of accumulated mining waste exceeds billions of tons. Up to 1 billion m^3 of mineralized water is pumped out of mines every year [18]. Today, the bulk of such waste cannot be considered as mineral resources, as it cannot be used in industry. On the other hand, their use requires transportation, which is associated with additional costs and makes raw materials uncompetitive. The hundreds of millions of tons of waste accumulated in Ukraine can significantly improve the mineral base of enterprises that extract building stones, raw materials for building ceramics, building sands, and ceramic clays, carbonate raw materials, etc., or drastically reduce the need to open new quarries of building materials.

The waste of primary processing (enrichment) of raw materials is various sand and sand-clay sludge. The volumes of this waste in the regions of Ukraine are measured in hundreds of millions of tons. For example, in Kryvbas area, reserves of sludge from the enrichment of iron ores exceed 1 billion tons. Waste from secondary processing of raw materials is accumulated in significant quantities at enterprises of ferrous metallurgy enterprises (blast furnace slag, ferroalloy slags, iron-containing waste), thermal power industry (ash and slag from burning coal), chemical, petrochemical, coke-chemical industries (phosphogypsum, pyrite cinders, liquid organic and inorganic waste), etc. Often, the content of mining waste in such elements as copper, cobalt, molybdenum, zinc, and others makes them suitable for use in agriculture as agronomic ores.

The density of accumulated waste in Ukraine is 6.5 times higher than in the USA and 3.2 times higher than in the countries of the European Union. Every year, more mining waste accumulates in Ukraine than in 12 EU countries. Donetsk, Dnipropetrovsk, Luhansk, Lviv, and Zaporizhzhia regions should be singled out (table 2). In the densely populated areas of Donbas, Kryvbas, Pre-Dnieper and Pre-Carpathian regions, the level of technogenic load ranges from 2-3 to 10-30 million t/km^2. Table 3 shows the volumes of technogenic waste accumulated within the main mining basins of Ukraine, which account for 79.2% of the total amount of waste [17].

Table 2. Volumes of mining waste in the administrative regions of Ukraine (on the materials of the Ministry of Ecology and Natural Resources of Ukraine).

Administrative units	Dump area, ha	Annual waste volume, million m^3	Volumes of annual waste use million m^3	Volumes of accumulated waste million m^3
AR of Crimea	17.0	0.10	0.05	1.52
Vinnytsia region	985.0	6.21	1.94	26.33
Volyn region	251.0	1.93	0.23	35.14
Dnipropetrovsk region	18,331.0	245.08	50.86	2,013.40
Donetsk region	12,284.7	127.60	22.82	2,771.14
Zhytomyr region	2,187.7	15.82	6.70	71.20
Transcarpathian region	27,5	0,48	0,23	3,89
Zaporizhzhia region	1,175.3	2.18	0.51	63.30
Ivano-Frankivsk region	384.2	5.94	2.37	86.81
Kyiv region	146.0	1.30	0.16	32.51
Kirovohrad region	953.6	10.71	1.72	128.00
Luhansk region	4,819.2	32.21	4.56	596.27
Lviv region	4,591.5	48.95	3.52	1,054.20
Mykolaiv region	39.3	0.58	–	3.12
Odesa region	160.6	0.26	0.60	5.34
Poltava region	4,440.6	40.59	3.86	591.80
Rivne region	276.9	2.41	0.69	24.65
Sumy region	63.5	0.84	0.46	6.98
Ternopil region	74.8	1.34	0.36	10.45
Kharkiv region	512.4	2.64	0.38	11.09
Kherson region	90.0	1.55	0.52	0.76
Khmelnytskyi region	201.8	5.43	1.93	95.46
Cherkasy region	796.5	1.28	0.59	8.67
Chernihiv region	224.0	0.12	0.19	1.46
Chernivtsi region	94.6	0.12	0.09	0.43
Total	53,128.4	554.67	105.33	7,643.92

Ukrainian enterprises generate up to 100 million tons of toxic waste every year, of which more than 3 million tons belong to I-III hazard classes. The total amount of toxic waste accumulation is 4.4 billion tons. In Ukraine, there is no plant for the processing of toxic industrial waste or landfills for their disposal. The conditions of waste storage and disposal do not meet sanitary and hygienic requirements and are one of the factors of intense pollution of atmospheric air, surface, groundwater and soil. It is also worth mentioning the illegal shipment of 25,000 tons of acid tars into Lviv region; the problem of their disposal has not been resolved by today. In the developed countries of the world, a considerable attention is paid to the issue of effective use of mining waste, and the level of their utilization is 65-80% [8]. In Ukraine, this indicator

Table 3. Volumes of accumulation of industrial waste in the main mining basins of Ukraine [17].

Mining basin	Area of disturbed geosystems, km^2	Volumes of accumulated waste, billion tons	Inflows of mine and quarry waters, billion m^3/year
Donetsk coal (Donbas)	15,000	9.4	788.4
Lviv-Volyn coal	150	0.5	6.2
Dnipro brown coal	38	0.2	–
Kryvyi Rih iron ore (Kryvbas)	170	7.5	–
Pre-Carpathian sulphurous	160	2.6	45.6
Pre-Carpathian saline	24	0.4	2.0
Total	15,542	20.6	–

is estimated to be only 10-12%, there for we have accumulated unused reserves of secondary mineral raw materials.

For the sustainable development of Ukraine, it is necessary not only to develop new reserves of natural raw materials, but also to develop technogenic mineral resources accumulated in more than 1,600 technogenic deposits and objects. Technogenic deposits contain non-ferrous, rare, noble, ferrous metals, rare earth elements, non-ore, construction and energy raw materials, limestone and gypsum meliorants, etc. These components can be removed using the latest technologies. Every year, a technogenic mass accumulates on the earth's surface: 350 million tons of iron, 7.4 million tons of phosphorus, 5.7 million tons of copper, 2.8 million tons of lead, 2.5 million tons of barium, 230 thousand tons of uranium, 190 thousand tons of arsenic, 7.9 thousand tons of mercury [19].

The simplest technological option remains the organization of waste disposal for the production of building materials. A list of construction materials, magnesium and sulfur-containing fertilizers, limestone and gypsum meliorants can be compiled from mineral raw materials waste in Ukraine. It is also possible to additionally obtain coal fuel, ferrous, non-ferrous, rare metals, and fluxes from industrial waste, which is important in conditions of acute shortage of raw materials. The development of technogenic deposits in Ukraine makes it possible to expand the mineral base of the mining industry by 15-20%. Up to 30% of overburden and host rocks removed from the subsoil, as well as waste from their enrichment, can be used for the production of building materials [17].

The problem of effective use of hydro-mineral raw materials is important. It is possible to extract industrial quantities of lithium, boron, germanium, etc. from underground mine waters. For example, the underground waters of Donbas contain from 0.152 to 0.355 mg/dm^3 of bromine, which exceeds the minimum industrial values of bromine by 20-60 times, germanium by 5-8 times, and lithium by 2 times. It is necessary to continue studying the distribution of useful elements and components in mine waters and developing technologies for their extraction [19]. Radioactive waste burial grounds should also be considered as deposits of technogenic raw materials. With a higher level of technological development, they can serve as a source for the extraction and enrichment of radioactive elements.

The main mass of disposed mining waste is used for backfilling spent quarry areas and mine sites, reclamation of disturbed lands. In the backfilling process, not only waste rock is used, but also industrial waste, which can be processed into useful products. However, the technical level of extraction and use of these wastes is insufficient to establish their rational use.

In the main mining regions of Ukraine, there are dozens of technogenic mineral deposits that are preliminarily prepared for processing, which will significantly reduce the cost of their development. According to some estimates, with modern technologies, about 40% of industrial waste can be used to obtain useful raw materials: commercial coal, ore concentrates, cement, building materials, coagulants, chemical meliorants, etc. The Geological Service of Ukraine registered 1,500 industrial waste accumulation sites. Among them, only 13 sites have the status of technogenic deposits (one is being developed), the rest are tentatively classified as potential deposits or technogenic manifestations [12]. According to the amendments to the legislation in the field of waste management, the number of industrial technogenic deposits may reach two or three hundred.

Solving the problem of mining waste as one of the components of the state environmental policy is envisaged by achieving Sustainable Development Goal 12 “Responsible consumption and production”. By 2030, it is planned to reduce the share of landfilled waste to 35.0% of the total volume of generated waste (in 2015, it was 50.0%). At the same time, the number of enterprises where hazardous substances management systems have been implemented should be brought up to 100.0% of the total number of enterprises that use them. Achieving the goal in terms of waste is expected through the use of innovative technologies, which is defined by national task 12.4 “Reduce the volume of waste generation and increase the volume of its processing and reuse based on innovative technologies and production”. The processing of secondary mineral raw materials from mining waste requires significant investments. Solving the problem of attracting foreign investments for the development of the mining industry complicates the Russian-Ukrainian war and the difficult economic situation in Ukraine.

Effective use of technogenic mineral raw materials will ensure [18]: 1) reduction of costs for the search of new and exploration of exploited mineral deposits; 2) preservation of non-renewable mineral raw materials, extension of the life of mining enterprises; 3) production of additional volumes of cheap precious metals, non-metallic and construction materials, etc.; 4) filling of mine and quarry mine sites, planning of post-mining landscapes, carrying out reclamation and revitalization; 5) reduction of anthropogenic load on disturbed territories; 6) release and rational use of land occupied by mining waste storage facilities, elimination of sources of pollution of the natural environment; 7) attraction of investments and improvement of equipment and raw material processing technology.

The use of energy- and resource-saving technologies in the mining sector will improve the environmental situation in Ukraine. The latest technologies are proved to be effective within a short period of time and ensure the maximum output of the final product per unit of raw mineral. The cost of commercial products from mining waste is 5-15 times lower than from ores extracted by traditional methods from natural mineral deposits [20]. Solving the problems of rational use of mineral raw materials is also related to the development and implementation of waste-free technologies. Today, the involvement of man-made waste in production processes is restrained by the low economic capacity of the state.

The accumulation of significant amounts of mining waste in Ukraine is a consequence of the irrational use of certain useful components. Under the condition of comprehensive use of mineral resources, the amount of waste will be reduced by two times. Such comprehensive use allows to increase the amount of obtained industrial raw materials and is of a great economic importance. The reform and development of the mining industry should be based on principles that meet modern economic and environmental requirements.

In recent years, numerous cases of unauthorized use of subsoil and other violations of the legislation in this area have been recorded in Ukraine. Individual enterprises that extract local types of minerals (building stone, sand, loam, sand-gravel mixture, etc.) operate without special permits. There is an illegal development of coal, oil and amber deposits, as well as geological exploration of the subsoil. Geological control over the study and use of mineral resources should be strengthened.

Subsoil protection involves implementation of a set of measures for the complete removal of mineral resources from the subsoil and the maximum possible, economically feasible reduction of losses during their development. Legislation in the field of subsoil protection provides [21]: 1) provision of comprehensive geological study of the subsoil, prevention of unauthorized use of the subsoil; 2) rational extraction and use of reserves of minerals and components; 3) prevention of the negative impact of works related to the use of subsoil, the preservation of mineral reserves, mine sites and operated or mothballed wells, as well as underground structures; 4) protection of mineral deposits from flooding, waterlogging, fires and other factors affecting the quality of minerals and the industrial value of deposits or complicating their development; 5) prevention of unauthorized development of areas of mineral deposits and subsoil pollution during storage of oil, gas and other substances and materials, burial of harmful substances and production waste, discharge of wastewater.

In general, the activities of mining enterprises of Ukraine should be aimed both at the maximum extraction of minerals and the preservation in an undisturbed state of reserves that may become minerals in the future, as well as at bringing areas of land disturbed by mining operations into a condition suitable for further use.

Quantitative indicators of the wealth of Ukraine mineral resources, unfortunately, do not fully reflect the real state of the state's mineral base. Reserves of certain types of minerals, in particular oil and gas, are depleted and imported, the probability of discovering new large deposits is low, and the development of small deposits is unprofitable. Currently, Ukraine mainly has hard-to-reach reserves, the development of which is becoming unprofitable, as well as a large mining industry with worn-out equipment, where the majority of the population is employed.

Ukraine is at the beginning of the stage of subsoil depletion. A high degree of geological study of the territory, the depletion of quality reserves of the main types of mineral raw materials, a low probability of discovering new large and even medium deposits in terms of reserves make it impractical to invest significant funds in prospecting and geological exploration. The technological re-equipment of the mining industry becomes a priority due to the high wear and tear of fixed assets.

Since the 1990s, the mineral base of Ukraine has experienced degradation in all its constituent parts. In particular, the overall production of minerals has fallen, the volume of prospecting and mining exploration decreased to critical values. The consequences of this "collapse" are felt even today. At the same time, a slow rate of decline in production of mining industries in the early 2000s made it possible to increase the share of production in the overall structure of industry by two times compared to 1990 (from 21.2% to 42.6%). During this period, the share of ferrous metallurgy in the overall structure of industry increased by 2.5 times, fuel industry – by 1.8 times, non-ferrous metallurgy – by 2.3 times. Despite this, production of oil with condensate decreased by 1.4 times, gas – by 1.6 times, coal – by 2.0 times, iron ore – by 2.2 times, and manganese ore – by 3.6 times. The main factor in the growth of the share of mining industries is the transition to world prices for mineral raw materials, the preservation of the markets for iron, manganese and titanium ores, facing stones and certain other types of minerals [19].

Subsoil depletion and the formation of an industry structure burdened by heavy industries are accompanied by significant long-term environmental consequences. This is due to saving on environmental costs at the stages of field development that gives a significant economic profit. At the same time, the costs for elimination of the consequences of emergency environmental situations, accidents, and disasters often exceed the profit from mineral raw materials sale.

The biased structure of the economy in the direction of heavy industries and depletion of the mineral base with the accumulation of negative environmental consequences contributed to the development of a deep economic crisis in the Soviet Union in the mid-1980s. Western countries experienced similar crises back in the 1970s, from which they came out by restructuring of their economy with the reduction of heavy industry and the development of knowledge-intensive industries. The economic crisis in most states of the post-Soviet space continues to deepen, and it is exacerbated by a long-lasting and powerful environmental crisis. Ukraine is still in a crisis situation today, despite some signs of stabilization of its economy that was actually achieved as a result of the stabilization of mineral raw materials mining. However, wear and tear of equipment at mining enterprises is very high (up to 70-80%). Due to imperfect technologies of extraction and mineral raw materials processing, unsatisfactory solutions of issues of comprehensive development of deposits, there are up to 70% of explored oil reserves, up to 50% of salts, up to 28% of coal, and up to 25% of metals that remain in the state's subsoil [22].

Ukraine may enter a period of technogenic emergency situations, accidents and catastrophes. Sustainable development of the mining industry can only be ensured by innovative activities. Technical re-equipment of mining enterprises should be carried out to reduce losses of minerals during their extraction and processing; as well as to ensure industrial safety.

The analysis of the mineral base of Ukraine gives reason to include into promising types such non-traditional mineral raw materials for the country as native gold, native copper, rare metals, vein quartz, and various types of precious, manufactured and decorative stones. With certain caveats, this list also includes diamonds, the prospects for opening their deposits have increased. It is predicted that these types of mineral raw materials, after detailed exploration and further exploitation, will lead to the improvement of the state's economic condition, the development of gold and copper ore, rare metal and quartz industries. To expand the prospects for the development of the mineral base, it is necessary to expand the development of such minerals as brown coal, shale gas, development of non-traditional energy sources, in particular gas-methane from coal deposits and gas hydrates.

Ukraine actively participates in the integration processes in the European and world communities. Most industries are related to the functioning of the domestic mineral base. The state's level of development affects the organization of exploration and exploitation of subsoil and the development strategy of its mining industry. Developed countries, even having their own mineral base, are focused on investing into the mining and processing of mineral raw materials in other countries and its import. Developing countries, on the contrary, count on the intensive use of their own mineral deposits for economic development and obtaining profits from the export of raw materials. The current state of the domestic economy is characterized by a significant export orientation of the mineral base and, at the same time, a high level of industry dependence on imported supplies of certain types of minerals, especially oil and gas.

The level of mineral reserves in Ukraine depends on many factors. An example is the situation with stocks of flux raw materials for metallurgical enterprises. Ukraine is provided with dolomite reserves for many years, but providing enterprises with high-quality raw materials is a difficult problem and is possible only by increasing extraction in Southern Donbas, which is currently occupied. An acute situation has developed with flux limestones, the main reserves of which are also concentrated in Donbas. Several large deposits lie at significant depths or occupy arable land, so a proper economic and ecological assessment of their exploitation options is required. Therefore, the prospects for discovering new deposits of high-quality raw materials are limited.

The state is interested in protecting the national producer and promoting the development of export-oriented industries. In Ukraine, industries that secure export growth and, accordingly, are sources for foreign hard currency flow into Ukraine, are material- and energy-intensive and are interconnected with the development and prospects of the mineral base. Today, subsidies are widely used to stimulate exports which causes various forms of dumping. In other cases, we have the export of minerals that have not been converted into a product of intermediate or final consumption. This leads to great losses for the economy of the state, since the prices of raw materials and final production differ by tens or even hundreds of times. This indicates a predatory attitude towards the mining industry and causes depletion of the subsoil without obtaining an economic effect.

In the development strategy of Ukraine, it is important to outline the directions of movement in the field of geological study and use of subsoil: 1) a need to build up reserves of mineral resources, provided that the balance reserves of minerals will be enough for hundreds of years; 2) a need to increase the volume of mineral extraction with significant reserves and complex geological conditions and adverse environmental consequences of the development of deposits; 3) to attract investments in the study of deposits of fuel and energy raw materials, both traditional (oil and gas, brown and hard coal, peat), and unconventional (shale gas, coal-bed methane, gas hydrates of the Black Sea shelf).

3. Conclusions

Analysis of modern approaches to solving the problem of effective mineral raw materials use and mining waste allows us to state the following.

1. Efficient use and protection of the subsoil is a part of rational nature management in the mineral base of Ukrainian regions and Ukraine as a whole. Rational nature management should be understood not only as the optimization of the processes of intensive use of natural resources and their protection, but also as a system of measures covering the protection and control of the state of the environment, the reproduction and preservation of these resources, the effective use of capital investments in mining enterprises, and the placement of productive forces in the region.
2. The components for the rational use of the subsoil include a comprehensive development of mineral deposits, a comprehensive use of mineral raw materials and mining waste, optimization of the structure of mining production and mineral raw materials consumption. The maximum satisfaction of society's needs in certain types of raw materials at specified costs and under the condition of compliance with environmental standards can be considered as a criterion for an effective and optimal use of mineral resources.
3. The rational use of mineral resources in the modern interpretation of this issue extends to all stages of their development, including the issue of waste disposal. Solving the waste problem is limited to covering those groups and types of subsoil resource processing waste that are direct substitutes for certain types of mineral resources. They are grouped under the name of mining waste.
4. A huge amount of mining waste has been accumulated in administrative regions of Ukraine, and the issue of their disposal has gone beyond just an economic and ecological problem and has acquired a significant socio-demographic significance. Mainly, this applies to densely populated areas of Donbas, Kryvbas, Pre-Dnieper and Pre-Carpathian regions, where waste density varies from 2-3 to 10-30 million t/km^2. There are no such similar loads in any country in the world.
5. Environmental problems have become particularly acute due to the accumulation of toxic waste, among which the most dangerous are heavy metals, petroleum products and acid tars. Ukrainian enterprises generate up to 100 million tons of toxic waste every year, of which more than 3 million tons belong to I-III hazard classes. The total volume of toxic waste accumulation is 4.4 billion tons. In Ukraine, there is no plant for the processing of toxic industrial waste or landfills for their disposal, and the conditions for storing and eliminating waste do not meet sanitary and hygienic requirements.
6. For sustainable economic development of Ukraine, it is necessary not only to develop new reserves of natural mineral resources, but also to utilize technogenic, secondary, and unconventional mineral resources, which are accumulated in over 1,600 technogenic deposits and objects. Technogenic deposits of various minerals represent a powerful reserve mineral resource base for the development of the mining industry. They contain non-ferrous, rare, precious, and black metals, as well as rare-earth elements, non-ore, construction and energy

raw materials, mineral fertilizers, limestone and gypsum ameliorants, and so on. The development of technogenic deposits in Ukraine would expand the resource base of mining and metallurgical, coal and mining-chemical industries by 15...20%. Up to 30% of extracted overburden and associated rocks, as well as waste from their beneficiation, can be utilized for the production of various building materials.

7. The comprehensive utilization of mineral resources can only be achieved through the development and implementation of advanced modern technologies in the areas of exploration, extraction, enrichment, and processing of raw materials. In general, solving the problem of rational use of mineral resources, as well as natural resources in general, is related to the development and implementation of waste-free technologies. A geological assessment of waste as technogenic deposits is also necessary (determining the nature of the distribution of useful components in waste masses, studying their technological characteristics, determining the amount of reserves, etc.). Only after carrying out a complex of such assessment works should the issue of ways and methods of waste utilization in specific territories be addressed. Priority should be given to environmental protection measures accompanying current mining-industrial production.
8. Currently, scientific research aimed at addressing such problems as improving existing and developing fundamentally new methods for extracting useful minerals from subsoil and useful components from complex mineral raw materials and mining waste; developing methodologies and technological schemes for studying the distribution of useful components in ores and enclosing rocks at the geological exploration stage; and developing an ecological and economic assessment of complex deposits, among others, remains relevant.
9. The main factors that have influenced the economic development of Ukraine, based on intensive and prolonged use of mineral resources, include: 1) gradual depletion of subsoil; 2) the formation of an economy skewed towards heavy industries; and 3) the accumulation of long-term negative ecological consequences. An economy deformed towards heavy industries requires four to five times more material, capital, energy, mineral, and other resources compared to economies with a balanced industrial structure, where a significant share is comprised of light industry, the service sector, and modern knowledge-intensive production. Depletion of subsoil and the formation of an industrial structure overloaded with heavy industries are accompanied by the accumulation of significant long-term ecological consequences.
10. Further development of Ukraine's mineral and raw material complex requires urgent resolution of state-level problems that significantly hinder the expansion of the mineral and raw material base, its ecological rehabilitation, and rational use. The current system of subsoil use in Ukraine does not meet the requirements of modern market economics, and there are no unified requirements or rules for subsoil use and determination of payments for their use in economic theory. Although Ukraine's mineral and raw material base has sufficient reserves of many types of valuable minerals, some of them are in the stage of depletion, which requires reform of the economic and ecological mechanism for using mineral resources. In strategic terms, it is important for Ukraine to determine the directions of movement in the field of geological exploration and subsoil use.

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References

[1] Syvyj M, Mazbayev O, Volik O, Panteleeva N and Hanchuk O 2021 *E3S Web Conf.* **280** 11012 URL `https://doi.org/10.1051/e3sconf/202128011012`
[2] Melnykov M 1987 *Mineral'no-syr'yevyye resursy i kompleksnoye ikh osvoyeniye [Mineral resources and their integrated development]* (Moscow: Nauka)
[3] Pedan M and Mishchenko V 1981 *Kompleksnoye ispol'zovaniye mineral'nykh resursov [Complex use of mineral resources]* (Kyiv: Nauk. dumka)
[4] Rekitar Y, Stepanova I and Romashina M 1975 *Effektivnost' ispol'zovaniya promyshlennykh otkhodov v stroitel'stve [Efficiency of using industrial waste in construction]* (Moscow: Stroyizdat)
[5] Bent O 1997 *Coal of Ukraine* **2** 56–57
[6] Rudko H and Shkitsa L 2001 *Ekolohiszna bezpeka ta razionalne pryrodokorystuvannia v mechach hirnyczopromyslovych I naftohazovych kovpleksiv [Ecological safety and rational nature management within the mining-industrial and oil and gas complexes]* (Ivano-Frankivsk: ZAT Nichlava)
[7] Andrievsky I 2004 *Strategic Panorama* **2** 88–95
[8] Galetsky L S, Polskoi F R and Petrova L O 2004 *Sci. Works of DonNTU. Min. and Geol. Ser* **81**(1) 111–117
[9] Komov I L 2004 *Sci. Works of DonNTU. Min. and Geol. Ser* **81** 11–24
[10] Panov B S 2004 *Sci. Works of DonNTU. Min. and Geol. Ser* **81** 3–7
[11] Rudenko L, Palienko V and Barshchevskii M 2005 *Ukr. Geogr. Mag* (3) 18–23
[12] Mishchenko V 2007 *Ekonomichni priorytety rozvytku ta rozshyrennya mineral'no-syrovynnoyi bazy Ukrayiny [Economic priorities for the development and expansion of the mineral raw materials base of Ukraine]* (Kyiv: Nauk. dumka)
[13] Udalov I V and Kononenko A V 2016 *Visnyk of V. N. Karazin Kharkiv National University, series "Geology. Geography. Ecology"* (45) 177–183 URL `https://periodicals.karazin.ua/geoeco/article/view/8212`
[14] Kilinska K and Kostashchuk V 2010 *History of Ukrainian Geography* (22) 128–134
[15] Rudko H, Ivanov Y and Kovalchuk I 2019 *Hirnychotekhnichni heosystemy Zakhidnoho rehionu Ukrayinyy [Mining geosystems of the Western region of Ukraine]* (Kyiv-Chernivtsi: Bukrek)
[16] Hrinov V H and Khorolskyi A O 2022 *Mineral resources of Ukraine* (2) 12–17 URL `https://doi.org/10.31996/mru.2022.2.12-17`
[17] Syvyj M, Paranko I and Ivanov Y 2013 *Geografija mineralnyh resursiv Ukrainy [Geography of mineral resources of Ukraine]* (Lviv)
[18] Danylyshyn B M, Doroguntsov S I and Mishchenko V S 1999 *Natural and resource potential of sustainable development of Ukraine)* (Kyiv: Nauk. dumka)
[19] Korzhneva V 2005 *Ecological Geology* (Kyiv: Kyiv University)
[20] Rudko H and Bondar O 2020 *Makroekolohiya Ukrayiny [Macroecology of Ukraine]* (Kyiv-Chernivtsi: Bukrek)
[21] 1994 Subsoil Code of Ukraine URL `https://www.resourcedata.org/dataset/rgi-subsoil-code-of-ukraine`
[22] Voytsikhovska A, Kravchenko O, Melen-Zabramna O and Pankevich M 2019 *The best European practices of waste management [Krashchi yevropeys'ki praktyky povodzhennya z vidkhodamy]* (Lviv: Manuscript)

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Investigation of constructive and technological parameters of an energy-efficient screw oil press

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Abstract. The article presents the investigation of constructive and technological parameters of an energy-efficient screw oil press. It is outlined the principle of operation of an energy-efficient screw oil press. The construction of the oil press is improved by the steam atomizer that is installed in the receiving hopper under the rifled rollers for moisture-thermal treatment with steam, which is completed with the heat exchanger, heating element, expansion tank and hydro group. Also, a steam generator connected to a steam atomizer which is embodied into the receiving hopper. It was analyzed the influence of the optimization criteria (oil yield, energy consumption and press productivity) on the efficiency of the technological process. These optimization criteria depend on the main independent factors: the length of the reception and preparation chamber, the material (sunflower pulp) moisture; the heating temperature, the screw rotation speed, the linear speed of movement of screw shaft turns. The optimal constructive and technological parameters of energy-efficient screw oil press are considered. The energy-efficient screw oil press refers to the equipment of the oil enterprises of small productivity and due to its design, it allows to use a simple technological scheme of oil pressing and to reduce the amount of energy and resources spent on the technological process in the context of use in sustainable food systems.

1. Introduction

At the current stage of economic evolution, in the conditions of the need to transfer the state's economy to an intensive path of development, the most rational use of production potentials is an urgent problem. One of the main tasks of sustainable food systems is the implementation of new technologies for the processing of agricultural products in the conditions of enterprises and farms as well as the production of small-sized, low-energy-consuming equipment for completing technological lines. In Ukraine sunflower is one of the most widespread agricultural crops. This is due primarily to the high profitability of crop cultivation, the possibility of effective sale of both seeds and vegetable oil. There are two methods to get oil from sunflower seeds: pressing and extraction method. However, the costs of producing oil by pressing are 8-10 times lower compared to extraction. All known types of screw presses can be divided into three groups: presses for preliminary and final removal of oil and double-acting presses (both types of removal of vegetable oil is carried out in one machine). The industry of such countries as the USA, Japan, India, China produces many options of oil presses. The geometric parameters of the oil presses, their kinematic and energy indicators are determined by the physical and mechanical properties of oil-containing seeds. Oil-separating presses can be part of oil raw material processing lines, or be independent units. However, according to the principle of action and work process, they are all of the same type. Oil presses that are used in the conditions of farms that process small volumes of sunflower have a number of disadvantages: low yield of oil in one pass, increased time spent on cleaning the press from clogging, which contributes to a significant decrease in the productivity and demands to manually push the oilcake from the hopper into the receiving and preparation chamber during repeated pressing, due to its poor flowability.

Food production is used as an entry point to improving food system sustainability [1]. Furthermore, it is important to provide the conceptual foundations of the mechanism of management of enterprise interaction with environment [2]. Ukrainian sunflower oil is export oriented product and positive trend on the world market will bring benefits for processing enterprises despite on uncertainty of country environment [3]. Various production sources including sunflower oil have the potential for producing improved food and fuel products such as biodiesel production and a renewable solvent phase [4]. Ukraine is one of the world-leading countries in production and export of sunflower oil and integration of the Ukrainian and the EU market is prospective way for economics and further biogas production [5]. The screw presses for different oil crops have almost identical principles of operation, but the technological regimes and constructive peculiarities can be varied [6]. There is some development of modern constructions of oil presses on the basis of analysis of the basic operational concepts for the screw channel and the influence of its parameters on the productivity [7]. It is considered the chemical, chromatography research carried out in the area of assessment of edible oils [8], also it was made a systematic review on effects of plant oil consumption [9]. The rapeseed and sunflower oil are most widespread not only in food technology but also in production of biogas, but there is a need to investigate different operating regimes [10] with use analysis methods to optimize the dimensional parameters and constructional characteristics [11]. The extraction method of processing vegetable oil is usually used in the conditions of big enterprises and there are a lot of issues [12], it is challenging during using high-moisture material [13]. The aspect of optimizing the processing technologies is important for the green manufacturing of oils [14]. It is important to take into account features of oil sunflower seeds and its input parameters [15]. There are a lot of by-products during processing sunflower oil such as press cakes and oil meal, which are high-protein feeds for farm animals [16]. The standardization of biomasses is going to be a key aspect to get good quality biofuels from those residues [17] and the thermal behaviour of these materials need to be studied [18]. With regards to the condition of pre- and post-processing techniques it is suggested to implement the new construction of expellers for oil millers in order to the fatty acid compositions of sunflower oil did not significantly change [19].

The screw presses have some common technical and technological drawbacks. The service condition of an oil screw press was analyzed. It was researched the fracture failure of the bearing rings [20]. Also, there were investigated the major components of the palm oil screw press [21]. The cases of shaft failure indicate common areas of failure that occur around the lower edges of the keyway and shaft shoulders [22]. The effectiveness of screw presses is evaluated for throughput capacity, feed rate, press cake oil content, oil expelling efficiency, percentage un-pressed grits output, percentage sludge output, and specific energy consumption [23]. The driveshaft of screw press is often found to be susceptible to failure, it is important to discover the root cause of this failure and the ways of its prevention [24]. The mechanical oil extraction using a commercial screw press was evaluated in the study [25]. The stress concentration occurred on the keyway of the tooth wheel holder, which finally caused the fracture at this area [26]. It is proposed to assess quality management systems through the values of the set of interconnected processes, to combine the assessments of different processes into one set of data and to estimate this set, which will allow assessing the system with higher objectivity and reliability, particularly in the conditions of enterprises of pressing sunflower oil [27]. The optimal constructive and technological parameters of technological equipment in the processes of agricultural production are considered [28], designing modern processing machines requires a study of the regularities of technological processes, dynamics and conditions of operation [29], but the investigation of constructive and technological parameters of an energy-efficient screw oil press was not the specific subject of research.

The aim of the article is to conduct the investigation of constructive and technological parameters of an energy-efficient screw oil press.

2. Methods

On the basis of the investigation of theoretical provisions of the process of oil separation by pressing sunflower seeds and engineering calculating methods it is proposed the constructive and technological parameters of an energy-efficient screw oil press.

In order to intensify the processing of sunflower seeds, the design of the screw press was improved, the laboratory and experimental studies of the pressing were carried out, the mathematical model on the basis of the main technological parameters has been developed. There was theoretically justified method of calculating the constructive and technological parameters of the screw press, conducted the factor ranking, the insignificant factors were excluded from further consideration.

The research outlined the optimization criteria and selected the coefficients of variation, according to which the optimal design and technological parameters of the energy-efficient screw oil press are presented. In the investigation were used the methods of generalization of theoretical and laboratory experimental studies, mathematical modelling of the process, substantiation of the method of processing experimental data, solution of the optimization problem in determining the constructive and technological parameters of an energy-efficient screw oil press [30].

3. Principle of operation of an energy-efficient screw oil press

The main process of the press method of obtaining oil is squeezing it from the sunflower pulp, which is a loose, porous material. At the beginning of the squeezing, as a result of the convergence of the particles, the oil, which was held on their surfaces, begins to flow through the channels between the particles. Then, with the onset of deformation of the particles, the oil begins to flow through the capillaries that make up the inner part of the particles themselves. From this moment the oil phase is considered continuous. Thus, the squeezing of oil from the sunflower pulp can be considered as the movement of an incompressible fluid in a porous, deformable medium. As the particles of the pressing sunflower pulp come together, the movement of the oil obeys the laws of hydrodynamics. When the oil is pressed deeply under high pressure, the surfaces of the sunflower pulp particles fuse with the encapsulation of the oil in separate areas of the cake. This phenomenon determines the uneven oiliness of the total mass of cake briquettes (shells). The part of the material, from which oil is squeezed out, undergoes elastic and plastic deformations during this process. As a result of the study of the influence of the character of the deformation on the degree of oil squeezing, it was found that the shear stress of the material created during squeezing should be less than the shear stress, which contributes to the emergence of plastic flow. This condition must be observed because in the case of plastic flow, together with the oil, the sunflower pulp will come out through the holes for its draining. At the same time, due to the drop in pressure, oil extraction will deteriorate.

When oil is squeezed out in screw presses, the pressure on the pressed material increases and the oil flows out not only due to the action of external conditions, but also as a result of the resistance of the sunflower pulp itself as it is compacted and the oil is squeezed out. In turn, the resistance of the sunflower pulp in the press depends on its plastic properties. When the sunflower pulp is over-dried, the formation of the cake into a shell stops and the pressed material begins to leave the press in the form of dry, stiff flour or groats with a high oil content. This transition is initially accompanied by an increase in the load on the drive electric motor of the press, and with the cessation of shell formation, its sharp drop. Often at this moment, structurally weak presses fail due to breakage of the most heavily loaded elements or stop under load, forming a pressing due to the failure of safety pins or tripping of protection. When the sunflower pulp is over moistened, the formation of the cake into a shell also stops and the pressed material comes out in the form of a shapeless soft mass. This transition is accompanied by a decrease in the load on the electric drive of the press. Thus, the pressure in the perforated cylinder is mainly depend on the plasticity of the sunflower pulp, the humidity and the temperature of the pressed material. In the process of pressing, the volume of the sunflower pulp is reduced due to the squeezing out of oil, convergence of the inner and outer surfaces of the particles, as well as due to some evaporation of moisture. The time the sunflower pulp stays in the screw press during squeezing depends on the speed of rotation of the screw shaft, the degree of capture of the material by the first turn of screw shaft, the physical and mechanical properties of the material and the degree of wear of the surfaces of the screw turns.

The energy-efficient screw oil press refers to the equipment of the oil and fat industry, namely to small-sized screw presses, which can be used in the enterprises of small productivity. During the development of an improved model, the task of creating a screw press for oil crops was set, in which, after crushing the seed core with rollers, the wet-thermal treatment of the sunflower seed pulp will be carried out using a steam-generating device. It will contribute to the improvement of the intensification of the separation of oil during pressing, and the process of steam heat treatment will not affect the quality of the oil. The energy-efficient screw oil press consists of a bed, a receiving hopper with rifled rollers, a perforated cylinder with slats collected in it, a screw shaft, a steam-generating device, a cone-type adjusting nut and a drive unit. The main attention during the development of the improved design was paid to the implementation of a steam-generating device, which makes it possible to intensify the separation of sunflower oil and thus increase its yield. The use of additional steaming will also contribute to the reduction of frictional forces and resistance of the processing material, which will allow to reduce the operation of the screw shaft and parts of the perforated cylinder and increase the service life of the press. The use of a steam-generating device for moisture-thermal processing makes it possible to increase the productivity of the press when processing oilseeds, reduce the oiliness of the cake, and increase the yield of sunflower oil.

The screw shaft is structurally made of individual screw turns, which differ in pitch and diameter, and intermediate rings, which are mounted on a smooth shaft and fixed against turning with a key. In the receiving hopper, there is a damper, a pair of threaded rollers, which receive a rotational movement from the screw shaft through a V-belt transmission. The main element of the press is the perforated cylinder, which has a welded cylindrical shape. Inside the cylindrical surface there are slats, which are held in place by a tension wedge. The installation of rifled rollers in the receiving hopper turns the sunflower seeds into a pulp, which contributes to the intensification of the oil separation process and the effective use of the perforated cylinder. Figure 1 shows a screw press for separating oil with a steam-generating device for wet-thermal processing; figure 2 shows a section of the receiving hopper with rifled rollers and a steam atomizer, a side view.

The screw press is fixed on the carcass 1. The material is fed into the receiving hopper 5, which is crushed by the rifled rollers 4, and turns into a sunflower pulp. The gap between the rollers is regulated depending on the physical and mechanical properties of the material being pressed. In the hopper, the sunflower pulp is subjected to moisture and thermal treatment with steam, the yield of the oil increases. In addition, the softening of the sunflower pulp will contribute to reducing the wear of the oil press parts. After moisture and thermal treatment, through the loading hole regulated by the valve 11, the material is sent to the middle of the reception and preparation chamber of the perforated cylinder 15, where it is captured by the turns of the screw shaft 13 and moves to the exit from the press. When the screw shaft rotates, the material is

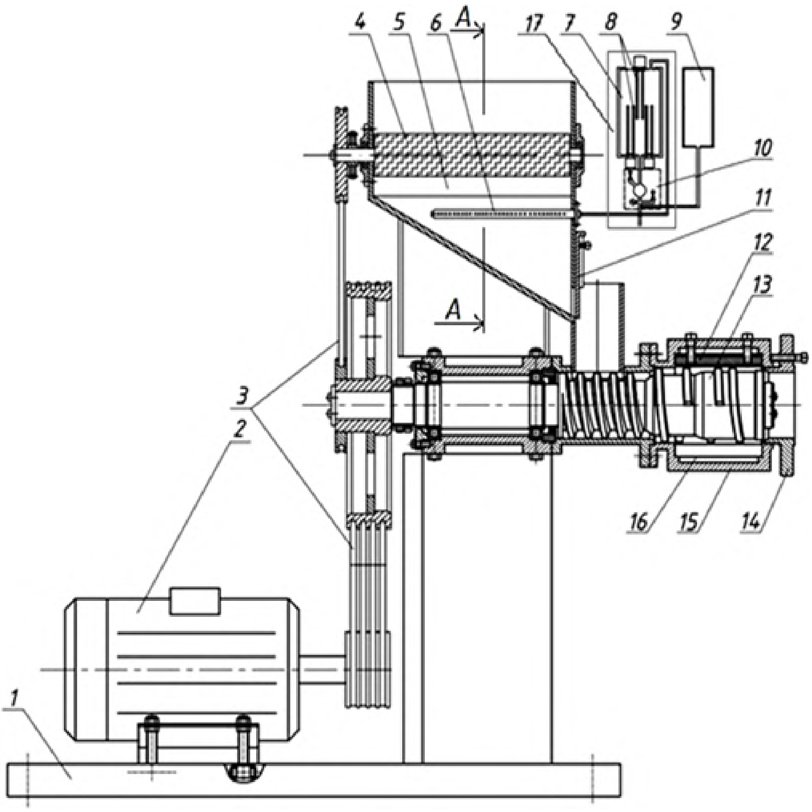

Figure 1. Energy-efficient screw oil press with a steam-generating device for wet-thermal processing: 1 – carcass; 2 – electric motor; 3 – V-belt transmission; 4 – rifled rollers; 5 – receiving hopper; 6 – steam atomizer; 7– heat exchanger; 8 – tubular electric heater; 9 – expansion tank; 10 – hydro groups; 11 – valve; 12 – tension wedge; 13 – screw shaft; 14 – adjustable nut; 15 – perforated cylinder; 16 – perforated panels; 17 – steam generator.

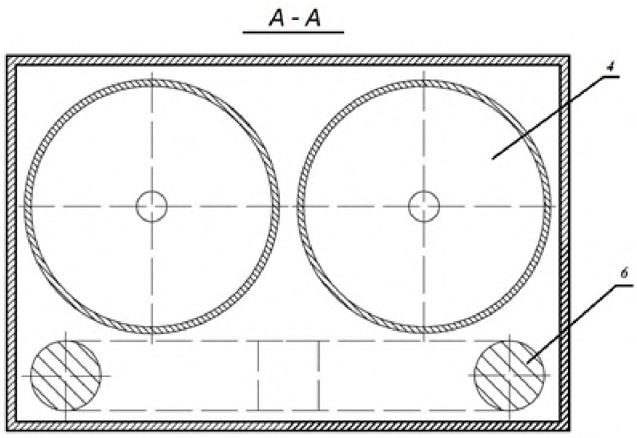

Figure 2. A section of the receiving hopper with rifled rollers and a steam atomizer: 4 – rifled rollers; 6 – steam atomizer.

transported into the working space, where oil is gradually squeezed out, which passes through the gaps between the perforated panels 16. Depending on the state of pressing material, the pressure in the working chamber is regulated using the adjustable nut 14. The area between the outer surface of the screw shaft and the inner surface of the perforated cylinder is the working space. Inside the cylindrical surface there are slats, which are held in place by the tension wedge 12. Steam generator 17 consists of: steam atomizer – 6; heat exchanger – 7; tubular electric heater – 8; expansion tank – 9; hydro groups – 10. The press and rollers are driven by the electric motor 2 through the V-belt transmission 3. Thus, the use of a steam-generating device in the design of the screw press will contribute to the intensification of oil separation to increase its yield, and will extend the service life of the structural elements of the machine.

4. Results

Analytical expressions obtained as a result of theoretical studies reflect an idealized technological process. Therefore, the purpose of research was to check the technological reliability, as well as quality indicators of the technological process according to three optimization criteria: maximum oil yield, minimum energy consumption, maximum press productivity. Achieving the set goal was carried out by solving a number of problems, for which: the factors that have the greatest influence on the quality of the technological process and are subject to regulation have been determined; the length of the reception and preparation chamber was increased and a steaming apparatus was installed in the experimental sample of the press; the dependence of oil yield (OY), energy consumption (EC) and press productivity (PP) on the identified variation factors was experimentally investigated. According to the results of optimization and determination of the optimal combination of factors on a sample of the screw press that operated as part of the sunflower seed processing line, the regularities of the technological process of pressing sunflower seeds were revealed.

At the initial stage of the study of any object using the theory of experiment planning, it is necessary, in addition to a thorough study of the literature, to conduct an a priori ranking of factors, which is performed by the method of expert evaluation. The essence of this method is in that the researchers are asked to arrange the factors that affect the progress of the process in the sequence of decreasing influence on the optimization criteria, that is, it is necessary to rank the correspondingly determined ordinal numbers (ranks) 1, 2, 3, $\ldots, k$. Factor ranking must be conducted in order to reduce the volume of experimental work, since insignificant factors can be quickly excluded from further consideration. This facilitates further stages of solving the experimental problem. The process of ranking the experiment is carried out as follows. During the interview, each specialist is asked to fill out a questionnaire, in which the factors, their dimensions and the expected intervals of variation of the factors are indicated. The specialist must assign the place of each factor, as well as supplement the questionnaire with other factors not included in the consideration.

The diagram of factor ranks shown in figure 3. There are chosen the factors: X1 – degree of crushing, mm; X2 – the length of the reception and preparation chamber, m; X3 – the width of the perforated channels, m; X4 – the working area of the perforated chamber, m^2; X5 – material (sunflower pulp) moisture, %; X6 – density of sunflower seeds, kg/m^3; X7 – heating temperature, C^0; X8 – screw rotation speed, s^{-1} ; X9 – linear speed of movement of screw shaft turns, m/s; X10 – level of mass input for pressing, kg/s; X11 – total area of perforated channels, m^2; X12 – the length of the perforated cylinder, m.

Conducted experimental studies showed that with an increase in press productivity, the oil yield ratio decreases, when extracting oil from the cake, oil drains along the entire length of the perforated chamber, it leads to clogging and stopping the press. The established facts allow to conclude that the sunflower seeds in the reception and preparation chamber do not have time to go into the state of pulp, that is, the material is not crushed enough and does not have enough time to heat up. Getting into the main chamber, this mass continues its transition into the sunflower pulp. Therefore, the initial part of the main chamber, almost to the middle, does not

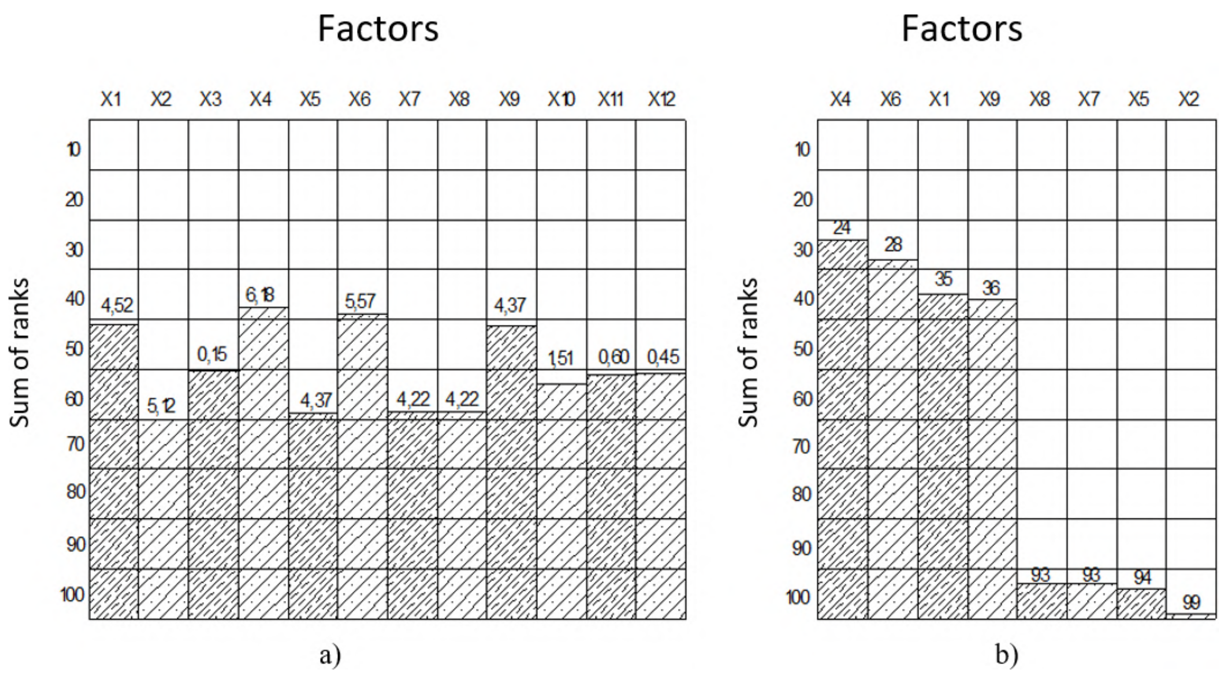

Figure 3. Ranking diagram of factors that affect the quality of work: a) to statistical assessment of the importance of factors; b) after ranking and determining non-significant factors.

work as intended, but performs the functions of a reception and preparation chamber.

In order to increase the efficiency of the process of extracting oil from sunflower seeds with a screw press it was enlarged the length of the reception and preparation chamber, that is, the conditions for obtaining high-quality crushed seeds were ensured. The particle size should be within 0.2-0.8 mm, and the heating temperature should be 80-125 $^{\circ}C$.

Obtained experimental data allowed to make an assumption that doubling the length of the reception and preparation chamber allows a significant increase in the percentage of oil yield.

In accordance with the experimental plan, an assessment of the dependence of technological process indicators, which have the greatest influence, was carried out. The most important indicators are: the length of the reception and preparation chamber, m (X2), the moisture content of the material (sunflower pulp), % (X5), the heating temperature, C^0 (X7), the speed of rotation of the screw shaft, s^{-1} (X8) and the linear speed of movement of the screw shaft turns, m/s (X9), which have the greatest effect on the quality of the screw press. The levels of setting of independent variables (factors) and the range of their variation adopted during the experiments are given in the table 1.

Table 1. Levels and range of variation factors.

Factors	Levels of variation			Interval of variation	Dimension
	-1	0	+1		
X_2	0	0.28	0.56	0.28	m
X_5	3	9	15	6	%
X_7	80	105	130	25	C^0
X_8	0.014	0.025	0.036	0.11	s^{-1}
X_9	0.002	0.04	0.006	0.002	m/s

The repeatability of experiments for each of the optimization criteria is three times. In each line of the plan, the average value of OY (oil yield), EC (energy consumption) and PP (press productivity) was calculated. Two-dimensional intersections of the response surfaces for the considered cases are shown in figure 4, figure 5 and figure 6.

With an increase in the length of the reception and preparation chamber and the humidity of the material (sunflower pulp), an increase in the percentage of oil yield and the productivity of the press is observed (figure 4). The zone of optimal combination of factors is limited by the arcs of the OY, EI and PP curves. The yield of oil will be in the range of 45-50 %; the energy consumption will not exceed 59 kW, and the press productivity will increase to 260 kg/h. For this technological regime, the speed of rotation of the screw shaft is equal to 0.025 s^{-1} , and the linear speed of movement of the turns of the screw shaft is 0.004 m/s.

The analysis of the results of the experiment demonstrates the higher quality of indicators of the technological process when the length of the reception and preparation chamber is 560

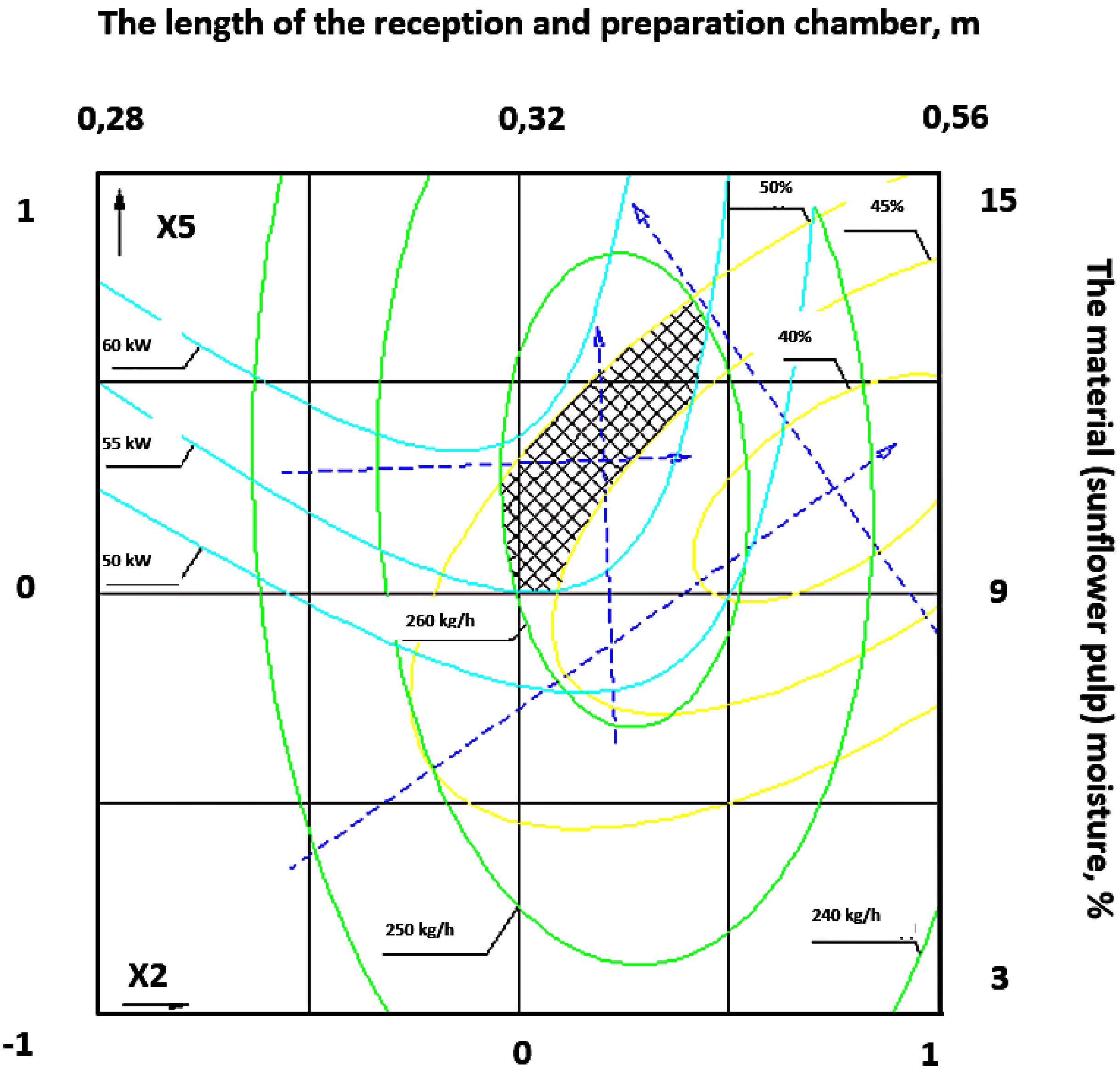

Figure 4. Two-dimensional intersections of response surfaces at X7=+1; X8=0; X9=0.

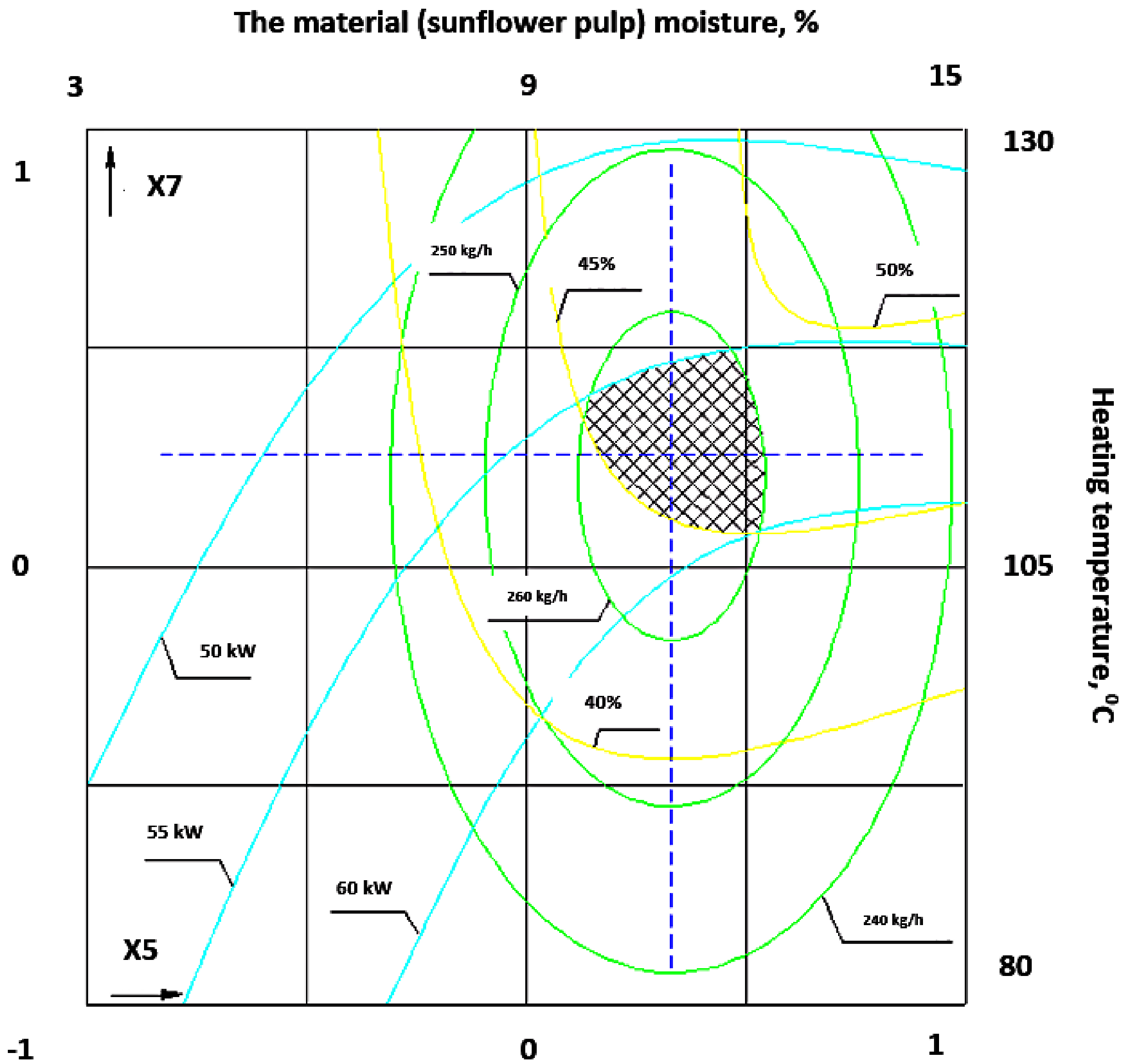

Figure 5. Two-dimensional intersections of response surfaces at X2=+1; X8=0; X9=0.

mm (figure 5). It is possible to achieve an oil yield of up to 50 % with an equipment power of 55-60 kW and a productivity of 260 kg/h. Humidity in the range of 9-15 % promotes better oil separation.

In order to achieve better values of the quality indicators of the technological process, compared to the two previously considered options, it is necessary that the length of the reception and preparation chamber be increased by 280 mm. As a result, it will be obtained more qualitatively crushed mass, and the pressing temperature is in the range of 105 – 130C^0 (figure 6). The selected combination of factors corresponds to the figure limited by the shaded area, the curves OY=50%, EC= 55kW and PP=260kg/h.

5. Discussion

In the context of the discussion of the obtained results it is necessary to point that the study of oil extraction process showed that the remaining oil in the sunflower pulp depends on the

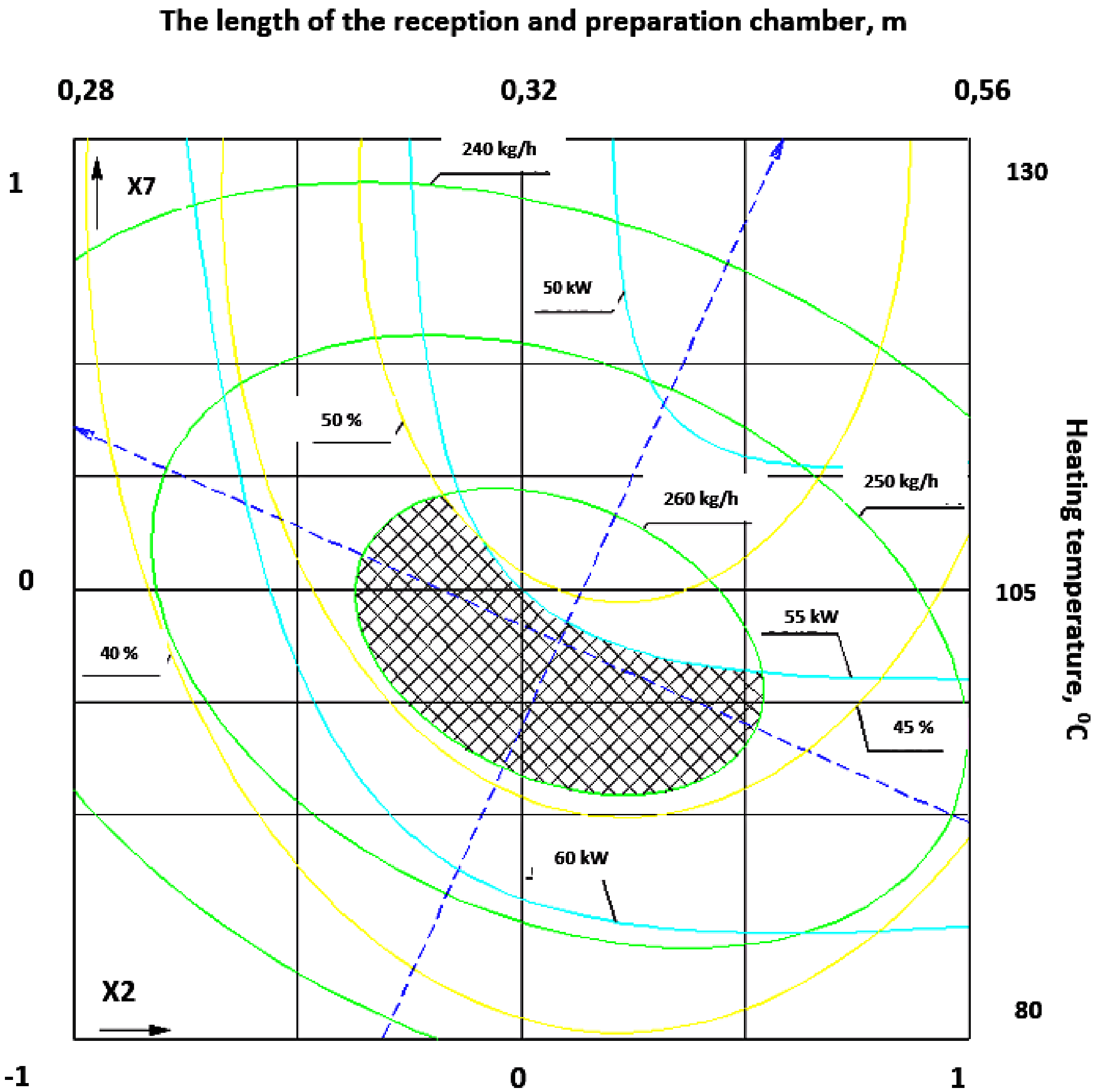

Figure 6. Two-dimensional intersections of response surfaces at X5=+1; X8=0; X9=0.

total and hydrodynamic pressure [31]. On the oil extraction process affect the thickness of the sunflower pulp layer, the permeability of the deforming sunflower pulp layer and its porosity, the viscosity of the oil, the duration of extraction, the degree compaction of the volumetric mass at the beginning and end of pressing and the density of the pressed oil [32]. Presses for extracting oil from vegetable raw materials have a similar principle of operation, but different constructive and technological parameters depending on the crop [33]. As well as the small enterprises or farms need the improvement of technological process indicators through the development of the energy efficient equipment in particular for producing sunflower oil [34].The squeezing of oil in the screw press occurs as a result of the gradual compaction of the sunflower pulp mass due to: reduction of the volume of mass located between turns, as a result of a gradual decrease in the pitch of individual turns and their height [35]. The mechanical effect of these turns on the sunflower pulp occurs during the rotation of the screw shaft [36]. The friction of the pressed material arises on the surface of the turns, the walls of the perforated cylinder and the friction of the particles among themselves [37]. Also, it is important to take into account the resistance of the mechanism that regulates the size of the outlet opening for the cake (cone, diaphragm, ring) [38]. The friction of the pressed material arises on the surface of the turns, the walls of the perforated cylinder and the friction of the particles among themselves [39]. The modernization of the energy-efficient screw oil press, namely the increase of length of the reception and preparation chamber and installation of steaming device can improve the indicators of the factors that determine the quality of oil extraction such as oil yield, energy consumption, press productivity, that was checked experimentally.

6. Conclusion

The technical solutions for pressing oil raw materials in the conditions of farms or small enterprises usually need the improvement of its efficiency. Also, they are not always technological when when it comes to increasing oil yield and equipment productivity. Thus, the urgent task is the production of small-sized, low-energy-consuming equipment for the completion of technological lines for the processing of agricultural products in the conditions of small enterprises in the context of food production sustainability. In order to eliminate these shortcomings, it is proposed to use energy-efficient screw oil press which consist of a carcass, a receiving hopper with rifled rollers, a perforated cylinder, a screw shaft, a steam-generating device, a cone-type adjusting nut and a drive unit.

The special feature of the design of screw oil press is that a steam atomizer is installed in the receiving hopper under the rifled rollers for carrying out moisture-thermal treatment. It is completed with a heat exchanger, a heating element, an expansion tank and a hydraulic group. Additionally, a steam generator connected to a steam atomizer that is implemented into the receiving hopper. The energy consumption of the pressing process is mainly influenced by the independent factors: the length of the reception and preparation chamber, the material (sunflower pulp) moisture; the heating temperature, the screw rotation speed, the linear speed of movement of screw shaft turns. The purpose of research is to check the quality indicators of the technological process according to the following optimization criteria: oil yield, energy consumption, press productivity. On the basis of theoretical and experimental studies, the most profitable constructional and technological parameters of the screw press have been established, namely: the length of the reception and preparation chamber is 560 mm, the moisture content of the pulp is within 9-15 %, and the pressing temperature is 130 $°C$. At the same time, the yield of oil is 45-50 %.

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References

[1] Obayelu A and Ayanshina S O 2020 Agricultural and Food Policy: Pathways to Sustainable Food Systems and Food Security *Developing Sustainable Food Systems, Policies, and Securities* ed Obayelu A E and Obayelu O A (IGI Global) pp 1–15 ISBN 9781799826019 URL https://doi.org/10.4018/978-1-7998-2599-9.ch001

[2] Ostapchuk T, Lehenchuk S, Denysiuk O, Orlova K and Biriuchenko S 2022 *IOP Conference Series: Earth and Environmental Science* **1049** 012043 URL https://doi.org/10.1088/1755-1315/1049/1/012043

[3] Makarchuk O 2022 *Bioeconomics and Agrarian Business* **12**

[4] Mazur V A, Pantsyreva H V, Mazur K Vand Myalkovsky R O and Alekseev O O 2020 *Agronomy Research* **18**(1) 177–182 URL https://doi.org/10.15159/AR.20.016

[5] Hamulczuk M, Makarchuk O and Kuts T 2021 *AGRIS on-line Papers in Economics and Informatics* **13**(3) 35–47 URL https://doi.org/10.7160/aol.2021.130304

[6] Kairbayeva A, Tlevlessova D, Imanbayev A, Mukhamadiyeva K and Mateyev Y 2022 *Eastern-European Journal of Enterprise Technologies* **2** 12–22 URL https://doi.org/10.15587/1729-4061.2022.255731

[7] Starkov A, Melnik G, Starkov K and Lisitsyn D 2022 *Processes and Food Production Equipment* 20–27 URL https://doi.org/10.17586/2310-1164-2022-15-2-20-27

[8] Sudhakar A, Chakraborty S K, Mahanti N K and Varghese C 2023 *Critical Reviews in Food Science and Nutrition* **63**(7) 873–901 URL https://doi.org/10.1080/10408398.2021.1956424

[9] Ghobadi S, Hassanzadeh-Rostami Z, Mohammadian F, Nikfetrat A, negar Ghasemifard, Dehkordi H R and Faghih S 2019 *Critical Reviews in Food Science and Nutrition* **59**(13) 2110–2124 URL https://doi.org/10.1080/10408398.2018.1438349

[10] Kapoor R, Ghosh P, Tyagi B, Vijay V K, Vijay V, Thakur I S, Kamyab H, Nguyen D D and Kumar A 2020 *Journal of Cleaner Production* **273** 123052 ISSN 0959-6526 URL https://doi.org/10.1016/j.jclepro.2020.123052

[11] Wang S, Yu Z, Aorigele and Zhang W 2022 *Computers and Electronics in Agriculture* **198** 107012 ISSN 0168-1699 URL https://doi.org/10.1016/j.compag.2022.107012

[12] Nguedap R D T, Tchuifon D R T, Conde M A, Mengounou G M, Ndom J C and Azebaze A G B 2020 *Chemical Science International Journal* **29**(6) 29–37 URL https://doi.org/10.9734/CSJI/2020/v29i630188

[13] Wang H, Wang R, Zhang L, Zhang W, Bakalis S, Li Y and Lametsch R 2023 *Food Research International* **163** 112286 ISSN 0963-9969 URL https://doi.org/10.1016/j.foodres.2022.112286

[14] Ye Z and Liu Y 2023 *Food Research International* **163** 112282 ISSN 0963-9969 URL https://doi.org/10.1016/j.foodres.2022.112282

[15] Hao J, Wei W, Huang P, Qin J and Zhao J 2021 *Nongye Gongcheng Xuebao/Transactions of the Chinese Society of Agricultural Engineering* **37**(12) 36–44 URL https://doi.org/10.11975/j.issn.1002-6819.2021.12.005

[16] Yegorov B, Turpurova T, Sharabaeva E and Bondar Y 2019 *Food Science and Technology* **13**(1) URL https://doi.org/10.15673/fst.v13i1.1337

[17] Perea-Moreno M A, Samerón-Manzano E and Perea-Moreno A J 2019 *Sustainability* **11**(3) 863 ISSN 2071-1050 URL https://doi.org/10.3390/su11030863

[18] Reinmöller M, Sieradzka M, Laabs M, Schreiner M, Mlonka-Mędrala A, Kopia A, Meyer B and Magdziarz A 2021 *Fuel* **301** 121026 ISSN 0016-2361 URL https://doi.org/10.1016/j.fuel.2021.121026

[19] Fouad M Gaber M A, Knoerzer K, Mansour M P, Trujillo F J, Juliano P and Shrestha P 2020 *Journal of Food Engineering* **284** 110053 ISSN 0260-8774 URL https://doi.org/10.1016/j.jfoodeng.2020.110053

[20] Zhou X, Zhang H, Hao X, Liao X and Han Q 2019 *Tribology International* **130** 289–298 ISSN 0301-679X URL https://doi.org/10.1016/j.triboint.2018.09.031

[21] Adetola O A, Olajide J O and Olalusi A P 2014 *International Journal of Scientific and Engineering Research* **5**(7) 1416–1422 URL https://www.ijser.org/researchpaper/Development-of-a-Screw-Press-for-Palm-Oil-Extraction.pdf

[22] Liu J, Ma C, Wang S, Wang S, Yang B and Shi H 2019 *International Journal of Machine Tools and Manufacture* **137** 42–57 ISSN 0890-6955 URL https://doi.org/10.1016/j.ijmachtools.2018.10.004

[23] Chew S C 2020 *Food Research International* **131** 108997 ISSN 0963-9969 URL https://doi.org/10.1016/j.foodres.2020.108997

[24] Muhammad I B, Husaini H, Ali N, Rauzatul A and Putra T E 2021 Failure Analysis of the Short Drive Shaft in a Screw Press Machine *Advanced Technologies in Material Processing II* (*Key Engineering Materials* vol 892) (Trans Tech Publications Ltd) pp 74–80 URL https://doi.org/10.4028/www.scientific.net/KEM.892.74

[25] Barati Z, Romuli S, Eberle T and Müller J 2022 Oil extraction from mango kernels using a mechanical screw press *Tropentag Conference 2022, Czech University of Life Sciences, Prague (CZU), Czech Republic, September 14 - 16, 2022* URL https://www.tropentag.de/2022/abstracts/posters/179.pdf

[26] Eaves T S, Paterson D T, Hewitt D R, Balmforth N J and Martinez D M 2020 *Journal of Engineering Mathematics* **120**(1) 1–28 ISSN 1573-2703 URL https://doi.org/10.1007/s10665-019-10029-3

[27] Trisch R, Gorbenko E, Dotsenko N, Kim N and Kiporenko G 2016 *Eastern-European Journal of Enterprise Technologies* **4** 18 URL https://doi.org/10.15587/1729-4061.2016.75503

[28] Dotsenko N A and Batsurovska I V 2022 *IOP Conference Series: Earth and Environmental Science* **1049**(1) 012047 URL https://doi.org/10.1088/1755-1315/1049/1/012047

[29] Shebanin V, Atamanyuk I, Gorbenko O, Kondratenko Y and Dotsenko N 2019 *Food Science and Technology* **13**(3) URL https://doi.org/10.15673/fst.v13i3.1480

[30] Bortz J and Döring N 2006 *Forschungsmethoden und Evaluation für Human- und Sozialwissenschaftler: Limitierte Sonderausgabe* 4th ed Springer-Lehrbuch (Berlin, Heidelberg: Springer) URL https://doi.

org/10.1007/978-3-540-33306-7
[31] Mursalykova M, Kakimov M, Kassenov A, Iskakov B, Sergibayeva Z, Kaspakov E, Zhumadilova G, Shulenova A, Kokayeva G and Suychinov A 2023 *Applied Sciences* **13**(5) 3057 URL https://doi.org/10.3390/app13053057
[32] Bhuiya M M K, Rasul M, Khan M, Ashwath N and Mofijur M 2020 *Industrial Crops and Products* **144** 112024 ISSN 0926-6690 URL https://doi.org/10.1016/j.indcrop.2019.112024
[33] Kovalyshyn S and Tomyuk V 2018 *BIO Web of Conferences* **10** 02011 URL https://doi.org/10.1051/bioconf/20181002011
[34] Shvets N, Shevtsova H, Pidorycheva I, Prokopenko O and Maslosh O 2023 *Agricultural and Resource Economics: International Scientific E-Journal* **9**(1) 260–282 URL https://doi.org/10.51599/are.2023.09.01.12
[35] Vasilachi C and Biris S S 2019 *E3S Web of Conferences* **112** 03022 URL https://doi.org/10.1051/e3sconf/201911203022
[36] Hu X, Zeng R, Li Y, Zhou J, Li X, Wang Y, Li X and Wang D 2022 *E3S Web of Conferences* **338** 01019 URL https://doi.org/10.1051/e3sconf/202233801019
[37] Kabutey A, Herak D, Ambarita H and Sigalingging R 2019 *Energies* **12** 2999 URL https://doi.org/10.3390/en12152999
[38] Ugarte-Espinoza P P, Delgado-Soriano V, Estivi L, Hidalgo A and Pascual-Chagman G 2021 *Italian Journal of Food Science* **33**(4) 107–117 URL https://doi.org/10.15586/ijfs.v33i4.2123
[39] Rani G, Gangadhara R, Rao K and Teja M 2021 *E3S Web of Conferences* **309** 01155 URL https://doi.org/10.1051/e3sconf/202130901155

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Geospatial modeling of the location of bomb shelters in residential areas of the city

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Geospatial modeling of the location of bomb shelters in residential areas of the city

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Abstract. The purpose of the article is to determine the optimal placement of the bomb shelter in the existing urban development. To achieve this goal, the authors used geoinformation systems. The authors set the task of processing topographic and geodetic data and related information. The authors implemented the task employing spatial analysis using existing ArcGis software modules. The use of the geoinformation system in the article makes it possible to significantly increase the speed of information processing than when using traditional methods. The use of the geoinformation system by the authors allows the creation of geodatabases with all the necessary attribute information. The authors researched the example of 522 micro-districts of the Saltivsky residential area of Kharkiv. The intellectual analysis of the existing information was carried out in this work using the geostatistical method for data transformation from a discrete to a continuous representation. In the article, the authors solved the task of determining the location of civil protection facilities using many factors and requirements. Visualization of the dangerous zones of the explosion of building debris during destruction, determination of the optimal route of movement of the population to the bomb shelter, and determination of the time required for this carried out. The obtained results, presented in the form of an algorithm, will make it possible to use the proposed sequence of actions to solve similar problems in the future. The authors developed an algorithm that significantly reduces the time for processing topographic and geodetic data and related information and solves the task of determining the location of civil protection facilities using many factors and requirements.

1. Problem statement

Determining the optimal location of a bomb shelter (object of civil protection of the population) in already formed residential areas is a time-consuming and long-term task. Such research relates to the formation of bomb shelters on a plot of land to protect the civilian population from the shrapnel effect of shells, debris from destroyed buildings, poisonous gases, and radiation.

Over the past 30 years, no one has investigated the problem of determining the optimal location of a bomb shelter. Bomb shelters were actively built during the Second World War and several years after its end. In that period of history, specially built bomb shelters were created and the basements of buildings in large cities were adapted for the protection of the population, and the use of underground subway facilities was planned.

After the collapse of the USSR, bomb shelters were no longer built, on the contrary, bomb shelters were only rebuilt or destroyed. Ukraine got the Soviet infrastructure with the lack of protective structures for the civilian population. Thus, the study of the issue of proper storage and operation of bomb shelters in Ukraine was not conducted.

The study of this topic is very relevant for all Ukrainian cities, as well as, for Kharkiv. Currently, during military operations, the issue of designing and building bomb shelters is relevant due to many rocket and artillery attacks on the civilian population. The research carried out by the authors showed that it is possible to design, build or place a room under a bomb shelter:

- in basements;
- in premises where it was previously planned to place parking spaces;
- at subway stations;
- in rooms on the first floor, protected from the outside by load-bearing walls and with the absence of window and door openings;
- in a new location determined with the help of GIS.

Today, most civil protection facilities are abandoned, in poor condition, or destroyed. In this regard, precisely during active hostilities, a problem arose related to the lack of reliable bomb shelters. In the article, the researchers consider the problem of designing bomb shelters in a new location determined with the help of GIS.

2. Literature review

The design of the optimal location of bomb shelters in residential areas with subsequent operation is subject to clause 16 of part 17 of the Civil Defense Code and clauses 11, 18, 19 [1]. This task is quite complex and requires the analysis of many factors and requirements. The procedure for the creation and maintenance of protective structures of civil defense and their record keeping was approved by the Resolution of the Cabinet of Ministers of Ukraine No. 138 [2].

For example, today, in one of the underground parking lots of the Kharkiv office center, converted into a bomb shelter, residents are hiding from dangerous shelling by Russian soldiers. The rooms of the bomb shelter have heating, ventilation, a storage tank with water, a certain supply of food, and even showers – everything necessary [3]. In the future, the design of new buildings with reinforced underground parking lots, which can be used as a reliable bomb shelter, is being considered. The mayor's office of Kharkiv, which suffered the most during the hostilities, prepared recommendations for developers on the arrangement of "safe rooms" using Israeli experience. A protective room with reinforced walls with a minimum area of 9 m^2 provided within the apartments. A new building should have a separate riser of such rooms, but the arrangement of these safe rooms will significantly increase the cost of the apartment. However, constant rocket and artillery attacks on the cities of Ukraine have shown that for the safety of the civilian population today, it is necessary to build new bomb shelters in populated areas.

Thus, today the government of Ukraine plans to introduce changes to building regulations. There is a need to consider Israel's experience in the planned reconstruction of housing, infrastructure, and bomb shelters. The issue of security is planned to be regulated at the legislative level with prescribed norms and rules [4].

Bomb shelters made of reinforced concrete are of great importance for the protection of people during hostilities. Functional requirements for such structures differ from ordinary residential or commercial structures. Therefore, other approaches are used for the design and construction of bomb shelters. For example, the explosion resistance of such structures should be maximum, especially in the conditions of hostilities, in such countries as Ukraine, Afghanistan, Israel, Syria, and Lebanon. There are developments in the use of ground explosion-proof sheltered cylindrical configurations consisting of vertical and inclined walls with a flat roof made of concrete and steel [5].

It is also necessary to add that the creation of bomb shelters or places to accommodate the population during natural disasters are costly project. The cost of the bomb shelter construction program depends on the population in the risk zone. Such a cost can be equal to the cost of a large military strategic system [6].

For houses that were built earlier, it is necessary to build separate bomb shelters where people can feel safe. The location of such civil protection facilities must be chosen carefully, based on many factors [7]. The issue of finding a city for a future bomb shelter is quite difficult because it is necessary not only to find a free place for construction in an already built-up massif but also to consider psychological and physiological factors of human life [8]. An important feature is that it is necessary to consider the fact that much of the young population either evacuated or is serving in the army, that is, most elderly people remained in the cities.

That is why great importance should be attached to the optimization of evacuation routes for vulnerable population groups when searching for a place to locate a bomb shelter. Also, it is important to develop a road map showing the routes to bomb shelters [9].

Emergency shelters, which provide places for temporary accommodation of the population during natural disasters, play a dual role, they can also be used as bomb shelters. Great attention should be paid to the optimization of location selection. It is necessary to pay attention to the experience of other countries. Special attention should be paid to the optimization of site selection issues using spatiotemporal regularities. Such storage facilities should be designed considering different types of natural disasters [10].

3. Materials and method

Currently, in the city of Kharkiv (Ukraine), as in most modern large cities, there are “sleeping” districts. The peculiarity of these compact places of residence of the population is that almost all the buildings are multi-story and quite close to each other. There are almost no undeveloped areas of the territory. Low-rise buildings (two- and three-story) – kindergartens, schools, and heat distribution stations are unevenly located in the district and in small numbers. To solve the goal set by the authors, namely, to determine the place of the optimal location of the bomb shelter in the already existing urban development, a typical micro district of the Saltivka residential area number 522 was chosen as an example (figure 1).

The peculiarity of this residential massif is the very compact living of people and the fact that the construction was carried out on alluvial soils and sands. The compositions decision of

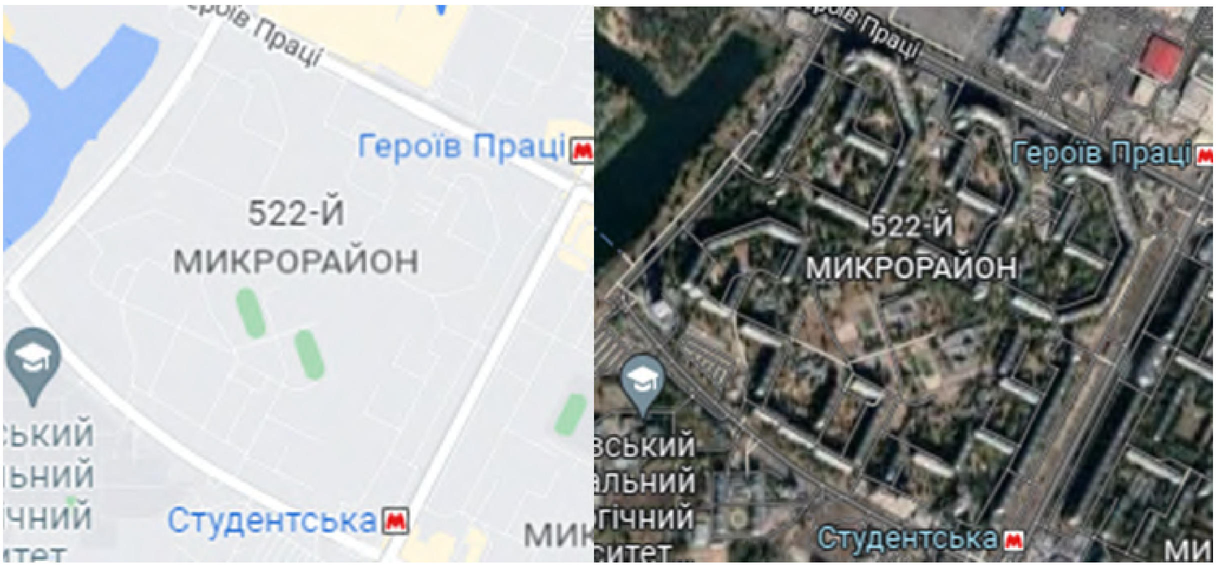

Figure 1. View of the 522nd micro district left – map; on right – is a satellite.

the designers was based on the discovery of plastic groups of rhythmically repeating buildings located along the central pedestrian alley leading to the Zhuravlivsky Hydro-park. The cultural and household services of this consolidated neighborhood were decided according to the principle of "focusing" [11]. Approximately 28,587 people live in the micro-district.

Choosing the location of a bomb shelter in such a densely populated neighborhood requires the processing of large volumes of diverse information and using information technologies designed for modeling spatial data. Modern means of analysis and visualization of territorial placement and modeling based on the use of geoinformation technologies [12, 13].

The main reason for the inclusion of geographic information systems (GIS) in solving the task of designing the placement of a bomb shelter is spatial analysis and decision support based on mathematical and cartographic modeling, visualization, forecasting, and evaluation. The use of

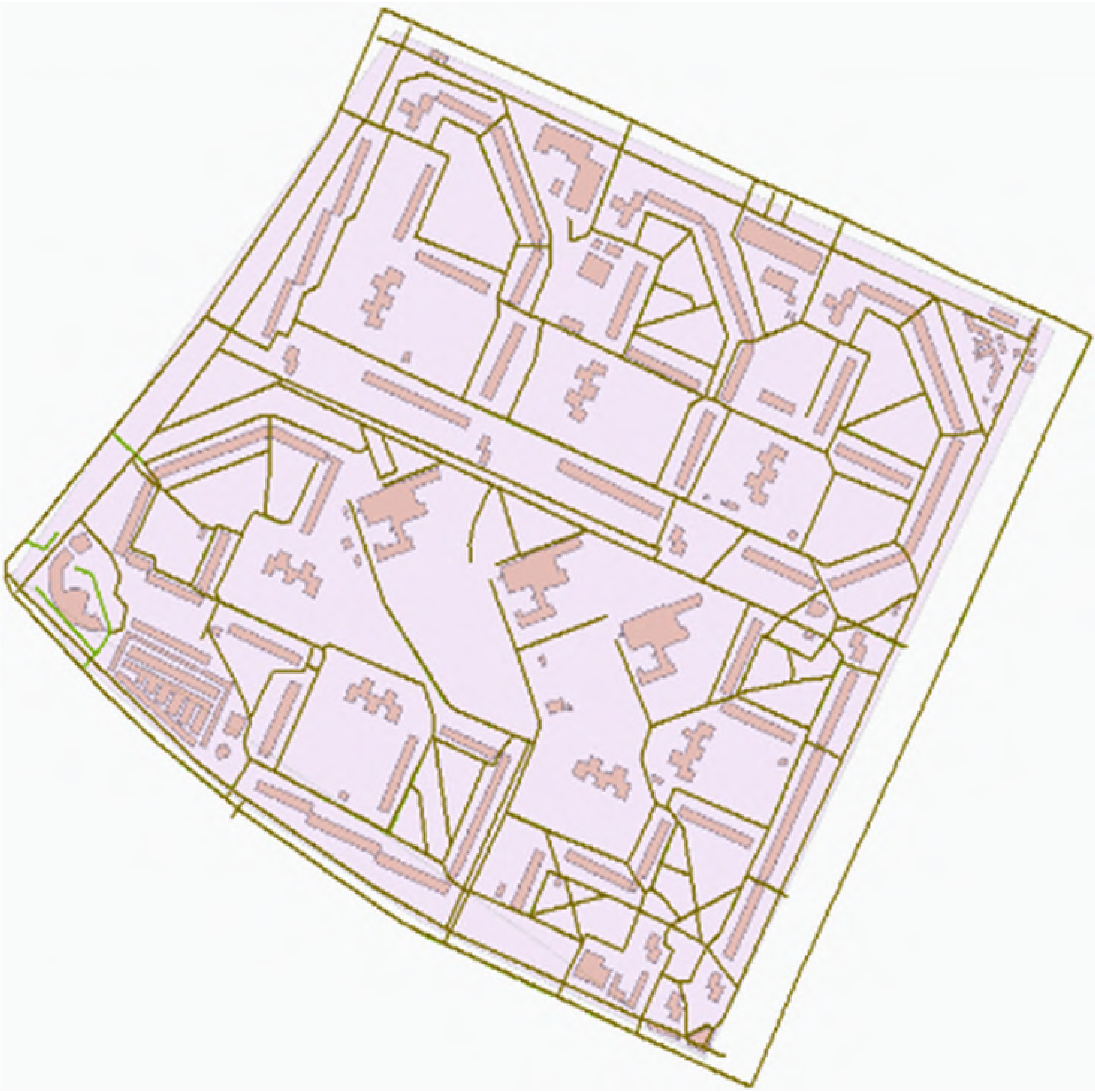

Figure 2. Digital model of the 522nd micro district.

GIS allows you to create a detailed visualization and conduct a qualitative spatial analysis [14,15] of the location of the bomb shelter concerning the territory. The simulation, the results of which are presented in this work, was done using the capabilities of the software product from the American company Esri – ArcGIS.

A personal geodatabase with the necessary layers was created to display the built-up objects of the micro-district. As a result of studying the necessary objects for further analysis, it was decided to use the following layers in the geodatabase:

- Layer Building1 (polygonal) – for displaying buildings.
- Layer Luki1 (point) – for displaying sewer hatches.
- Layer Polygon1 (polygonal) – for displaying the boundaries of the neighborhood.
- Layer Streets ND (dotted) – for displaying walking routes to the bomb shelter.
- Layer Streets1 (linear) – for displaying highways.
- Layer Streets2 (linear) – for displaying footpaths.

For all layers, the USC 2000 zone 7 coordinate system was set. The initial data for vectorization were the materials of the general plan of the Kharkiv. As a result, a digital model of the territory of micro-district 522 of the Saltivsky residential massif was created, considering residential and non-residential buildings (figure 2).

After vectorization, the data was entered into the attribute tables of the corresponding layers. These data will be needed in the future for calculations and analysis of the land plot. An example of a filled attribute table for a point layer of sewer hatches (Luki1) is shown in figure 3.

One of the important characteristics of the 522 micro district is the presence of two metro stations (Heroiv Pratsi and Studentska). During air raids and shelling, they can perform a

OBJECTID *	SHAPE *	SHAPE_Length	Cover type	Name_UKR
495	Polyline	29,050222	асфальт	вул. Валентинівська
496	Polyline	17,87193	асфальт	вул. Валентинівська
497	Polyline	71,75688	асфальт	вул. Валентинівська
498	Polyline	14,453158	асфальт	вул. Валентинівська
499	Polyline	11,294712	асфальт	вул. Валентинівська
500	Polyline	55,953125	асфальт	вул. Валентинівська
501	Polyline	22,341675	асфальт	вул. Валентинівська
502	Polyline	28,257557	асфальт	вул. Валентинівська
503	Polyline	43,845346	асфальт	вул. Валентинівська
504	Polyline	128,339538	асфальт	вул. Валентинівська
505	Polyline	21,654294	асфальт	вул. Валентинівська
506	Polyline	67,235544	асфальт	вул. Валентинівська
507	Polyline	65,853234	асфальт	вул. Валентинівська
508	Polyline	0,393661	асфальт	вул. Валентинівська
509	Polyline	1,090647	асфальт	вул. Валентинівська
510	Polyline	75,026269	асфальт	вул. Валентинівська
511	Polyline	71,437359	асфальт	вул. Валентинівська
512	Polyline	51,782354	асфальт	вул. Валентинівська
513	Polyline	55,643087	асфальт	вул. Валентинівська
514	Polyline	71,75249	асфальт	вул. Валентинівська
515	Polyline	99,128419	асфальт	вул. Валентинівська
516	Polyline	57,659617	асфальт	вул. Валентинівська
517	Polyline	80,930162	асфальт	вул. Валентинівська
518	Polyline	97,983407	асфальт	вул. Валентинівська
519	Polyline	52,147021	асфальт	вул. Валентинівська

Figure 3. The fragment of the attributive table with data on sewer manholes.

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protective function for people living nearby. There are also three three-story school buildings in the neighborhood. The peculiarity is that all three schools are located next to each other, and thanks to the presence of stadiums with football fields in two of them, all these schools are at a considerable distance from the adjacent residential development.

To mark on the digital map dangerous zones (on which debris does not fall in the event of a building collapse), it is necessary to calculate the distance of debris falling around the buildings. For this, we will use the following formula:

$$L = (E \cdot 2.9 + 1.5 + 2)/2.9 \tag{1}$$

where

E is the number of floors;

2.9 is the floor height;

1.5 is the height of the semi-basement;

2 is the height of the technical floor.

To determine the height of the only 25-story building in the neighborhood, you need to add 7.2 m, since the technical floor and semi-basement are much higher, unlike the buildings of the old version, which built the entire neighborhood. On the given fragment of the digital map (figure 4) the zones of debris spread around all the houses in the neighborhood are marked.

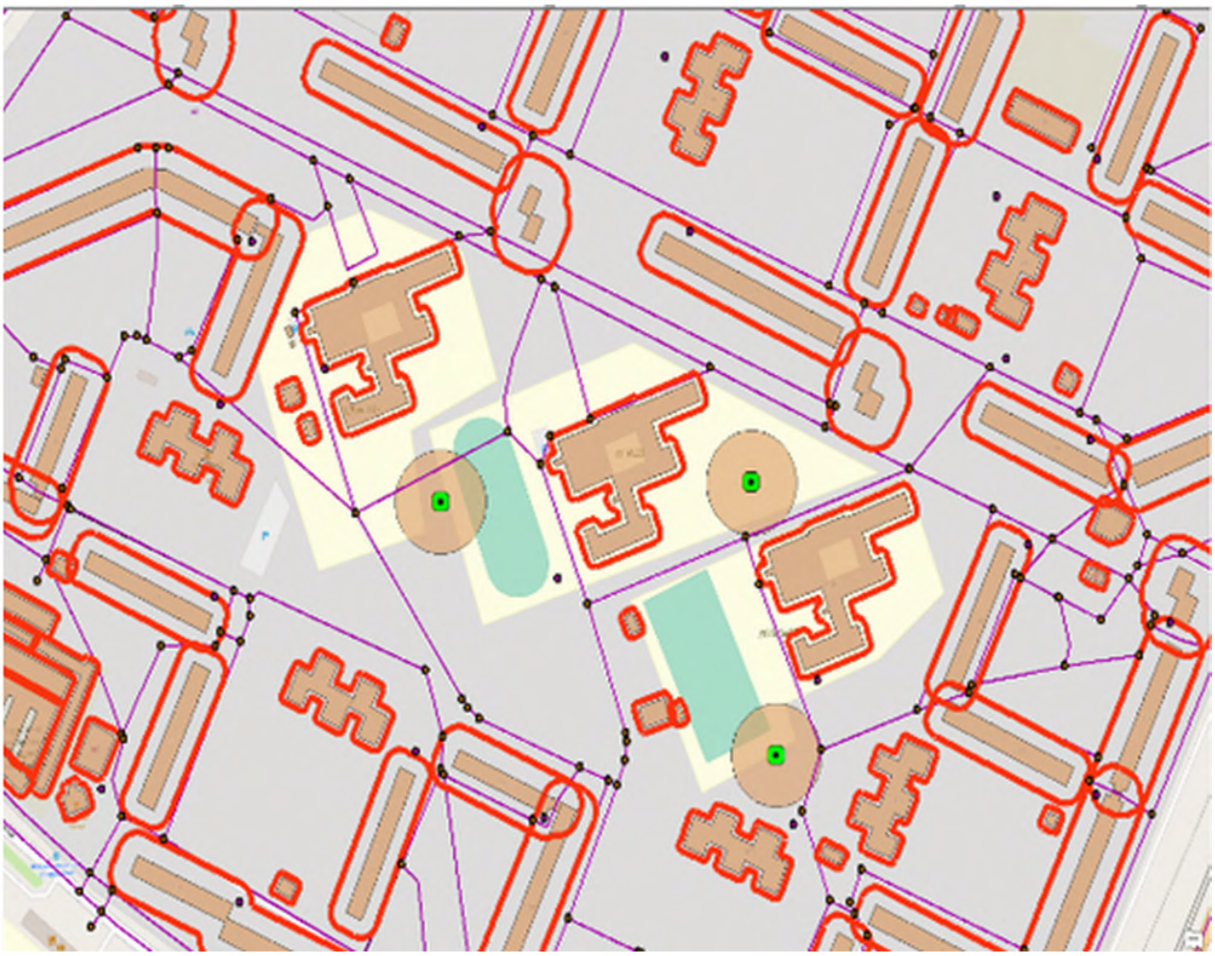

Figure 4. A view of the scattered debris zones around the houses.

From figure 4, from the south, schools are at a safe distance from residential buildings, and if they collapse due to the impact of shells, a large free area remains. Therefore, the authors proposed the creation of bomb shelters on the territory of school sports fields. The location of the bomb shelters themselves are marked on the digital map with dots. Thanks to the calculations carried out in the work, it is proposed to create three warehouses with 2500 places in each.

None of the bomb shelters fall into the area of the explosion of building debris, so the entrance to them not be blocked for the public. Three bomb shelters can accommodate 7,500 people. Approximately 28,587 people live in the micro-district. It means that approximately 30 percent of the population will be to stay in a safe place. The rest of the population can find shelter in the two existing metro stations.

In our opinion, a large civil defense structure should not be built, since, in case of damage to the bomb shelter with high-precision heavy weapons, it will not be possible to move the population to another shelter. In the case of a blockage of the entrance door of the protective structure due to a direct hit, several emergencies exit for evacuation are provided in each structure. And thanks to the fact that the three storage facilities are located next to each other, the civilian population will be able to quickly move to another storage facility. It is more appropriate to build three small bomb shelters, and place sports school grounds and stadiums on top of them. Thus, children are not left without the opportunity to conduct physical education classes in the open air.

To reach the bomb shelter in the event of an alarm, the civilian population needs approximately 15 minutes according to safety standards. Therefore, it is necessary to perform the following calculations for each of the four corners of the neighborhood and determine the time and optimal walking route. The Network Analyst module of the ArcGIS geographic information system was used for this task. The results of the analysis shown in the figure 5. Routes of movement to the bomb shelter from different ends of the 522 micro district and they demonstrate optimal routes from the northeast corner (10 minutes), from the southwest corner (11 minutes),

Figure 5. Routes of movement to the bomb shelter from different ends of the 522nd micro district.

from the southeast corner (4 minutes), from the northwest corner (15 minutes) (figure 5). As you can see, no route exceeds the 15 minutes recommended by regulations.

The received optimal walking routes to bomb shelters must be sent in advance to all residents of the neighborhood using social networks and printed and distributed.

One of the most important stages of determining the optimal place for a bomb shelter in an already existing residential building (figure 6) is the development of a geodatabase, which includes all the necessary factors for choosing the location of a civil defense facility.

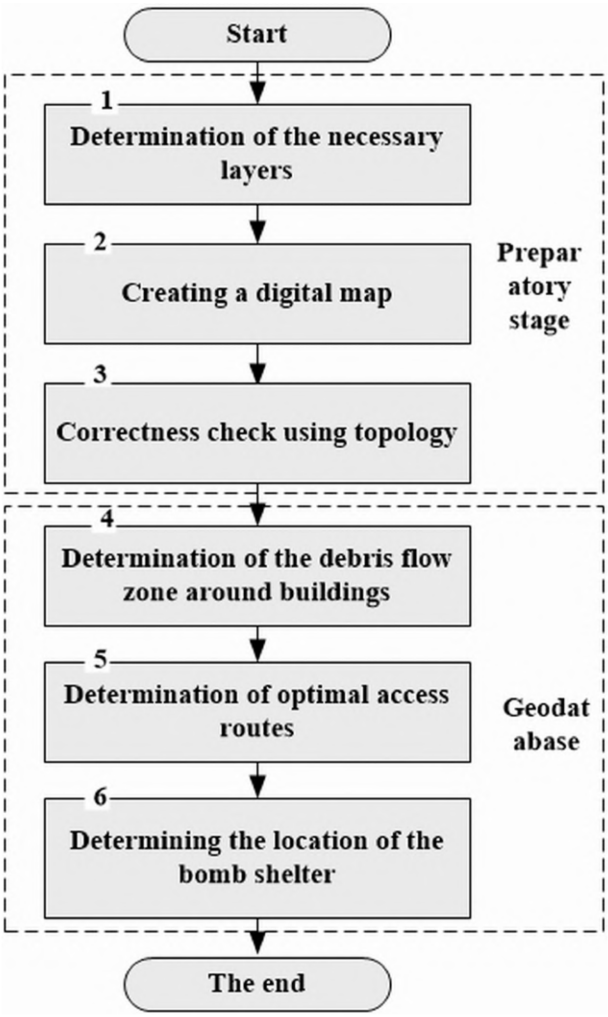

Figure 6. Algorithm for finding the optimal place for the location of the civil protection facility.

4. Results

1. The authors developed a digital geoinformation model of 522nd micro-district of the Saltivska residential area of the city of Kharkiv with the introduction of a significant amount of attribute data.
2. The optimal routes to the designed bomb shelters were calculated using geographic information systems and displayed on digital maps.
3. In the article, calculations are made regarding the distance of debris flying around buildings, and dangerous zones are displayed on a digital map.

4. Reference with the fact that the task of finding a place for the location of a civil protection facility in an already built residential area must be solved not only in Ukraine but also in many other countries of the world. An important feature of the work is that such a design was not foreseen at the stage of development of the master plan of the city's residential area. The authors have developed an algorithm for solving the task of finding a place for the location of a civil protection facility in an already built, crowded residential area.
5. In the research conducted by the authors, the locations of bomb shelters were determined based on the results of the analysis of many factors.

5. Conclusions

Thus, the geospatial modeling used by the authors made it possible to carry out actions to determine the optimal location of the protective structures of the civilian population. The calculations obtained by the authors enable the government and regional authorities to create a civil protection facility for the population in built-up areas.

The application of geoinformation technologies for modeling the optimal placement of bomb shelters in residential areas allowed for considering many factors, such as the spread of debris around buildings, and the optimal route of movement to the bomb shelter. That is, the authors proposed how to solve the task with minimal time expenditure and with the lowest probability of error. With the help of a spatial analysis performed in the ArcGIS geoinformation system, a place was chosen for the construction of a bomb shelter for the civilian population in the 522nd micro district of Kharkiv. A digital geoinformation model of 522 micro districts of the residential area of the city of Kharkiv has been developed.

In the work, with the help of the ArcGIS software package, a geodatabase of this neighborhood was developed, which made it possible to determine the number and location of civil protection facilities. In the future, it is possible to use the proposed sequence of actions to solve similar problems.

In general, the intelligent analysis of geostatic models can be used to process data in any locality thanks to the use of a geostatistical method to transform data from a discrete to a continuous representation.

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References

[1] Verkhovna Rada of Ukraine 2013 Code of Civil Protection of Ukraine URL https://zakon.rada.gov.ua/laws/show/5403-17?lang=en#Text
[2] Cabinet of Ministers of Ukraine) 2011 Pro zatverdzhennia Poriadku vidrakhuvannia do derzhavnoho biudzhetu chastyny chystoho prybutku (dokhodu) derzhavnymy unitarnymy pidpryiemstvamy ta yikh obiednanniamy URL https://tax.gov.ua/zakonodavstvo/podatkove-zakonodavstvo/postanovi-kabinetu-ministr/73403.html
[3] Orlova V 2022 Bomboskhovyshcha-parkinhy ta ukryttia v dytsadkakh: Terekhov pro maibutniu rekonstruktsiiu Kharkova [Bomb shelters, parking lots and shelters in kindergartens: Terekhov about the future reconstruction of Kharkov] URL https://cutt.ly/ZwduP6Cl
[4] Melnyk S 2022 U Lvovi zatverdyly novi standarty budivnytstva zhytla [New housing construction standards approved in Lviv] URL https://www.epravda.com.ua/news/2022/05/15/687058/
[5] Anas S M, Alam M and Umair M 2023 *Materials Today: Proceedings* **74** 547–568 ISSN 2214-7853 3rd International Conference on Recent Advances in Mechanical Engineering Research and Development URL https://doi.org/10.1016/j.matpr.2022.09.125
[6] Wei Y, Jin L, Xu M, Pan S, Xu Y and Zhang Y 2020 *International Journal of Disaster Risk Reduction* **51** 101813 ISSN 2212-4209 URL https://doi.org/10.1016/j.ijdrr.2020.101813

[7] Rozenblat S and Iecovich E 2013 *European Journal of Ageing* **10**(1) 61–70 ISSN 1613-9380 URL https://doi.org/10.1007/s10433-012-0249-1
[8] Bernhardsson S and Forsén R 2013 Assessment of Damage and Protective Capacity of Buildings Exposed to Weapon Effects *2013 European Intelligence and Security Informatics Conference* pp 222–222 URL https://doi.org/10.1109/EISIC.2013.54
[9] Chester C V and Zimmerman G P 1987 *Tunnelling and Underground Space Technology* **2**(4) 401–428 ISSN 0886-7798 URL https://doi.org/10.1016/0886-7798(87)90101-5
[10] Esposito Amideo A, Scaparra M and Kotiadis K 2019 *European Journal of Operational Research* **279**(2) 279–295 ISSN 0377-2217 URL https://doi.org/10.1016/j.ejor.2018.12.009
[11] Tseng F Y, Chao C J, Yau Y J and Feng W Y 2018 *Displays* **51** 36–42 ISSN 0141-9382 URL https://doi.org/10.1016/j.displa.2017.11.001
[12] Pomortseva O, Kobzan S, Yevdokimov A and Kukhar M 2020 *E3S Web of Conferences* **166** 01002 URL https://doi.org/10.1051/e3sconf/202016601002
[13] Pomortseva O, Kobzan S, Voronkov O and Yevdokimov A 2021 **280** 11013 URL https://doi.org/10.1051/e3sconf/202128011013
[14] Voronin V O, Lyantse E V and Mamchyn M M 2006 *Analityka rynku nerukhomosti: metodolohiya ta pryntsypy suchasnoyi otsinky [Analytics of the real estate market: methodology and principles of modern evaluation]* (Lviv: Magnolia)
[15] Loza V, Kubiavka M, Nikiforov M, Zlatnikov V and Prylipko O 2019 Geoinformation system of monitoring and decision making support in the conditions of hybridization of modern warfare *Monitoring 2019* vol 2019 (European Association of Geoscientists & Engineers) pp 1–5

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The use of GIS technologies for geodetic monitoring

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The use of GIS technologies for geodetic monitoring

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Abstract. Using GIS technologies, the article analyzes, systematizes, and processes, the data obtained in the process of geodetic monitoring of man-made territories and objects, which will make it possible to analyze the existing state of the object and provide an opportunity to determine critical spatial deviations that can lead to irreversible processes of destruction of buildings and structures. This provides an opportunity to prevent processes that can lead to large-scale disasters, as well as determines the adoption of timely measures to prevent the destruction of structures and predict emergencies.

1. Introduction

On the territory of Ukraine, there are many potentially dangerous objects of the fuel and energy complex, hydraulic structures, industrial facilities, mineral extraction enterprises, and others, of which operational resource is almost exhausted. Therefore, any dangerous phenomena of an endogenous and exogenous nature (earthquakes, landslides, and floods), or man-made factors caused by human activity can lead to large-scale disasters. We must not forget about the energy issue of state security, which is currently gaining great importance. Therefore, a necessary factor in preventing the destruction of objects and predicting deformations of engineering structures is the use of GIS technologies for geodetic monitoring of man-made territories and objects.

2. Methodology

On April 26, 1986, the largest man-made disaster in the history of mankind occurred – the explosion at the Chornobyl nuclear power plant. In a short time – from July to November 1986 – a protective structure was erected over the destroyed fourth power unit of the Chornobyl NPP (a little later it received the unofficial name “Shelter”) to protect the environment from further pollution [1].

Since the “Shelter” facility was built within a short period and under extreme conditions, it does not comply with the rules and regulations for the design, construction, commissioning, and operation of either nuclear installations or radioactive waste management facilities, or regular industrial buildings. Therefore, after its construction, constant engineering, and geodetic monitoring of the state of the entire complex of buildings and structures of the “Shelter” facility became the key task.

The volume of engineering and geodetic observations of the “Shelter” facility includes the regular determination of the height position of the settlement control marks on the foundations and the spatial position of the deformation marks located, respectively, in the plinth (lower tier) and on the upper tiers of the “Shelter” facility (figure 1).

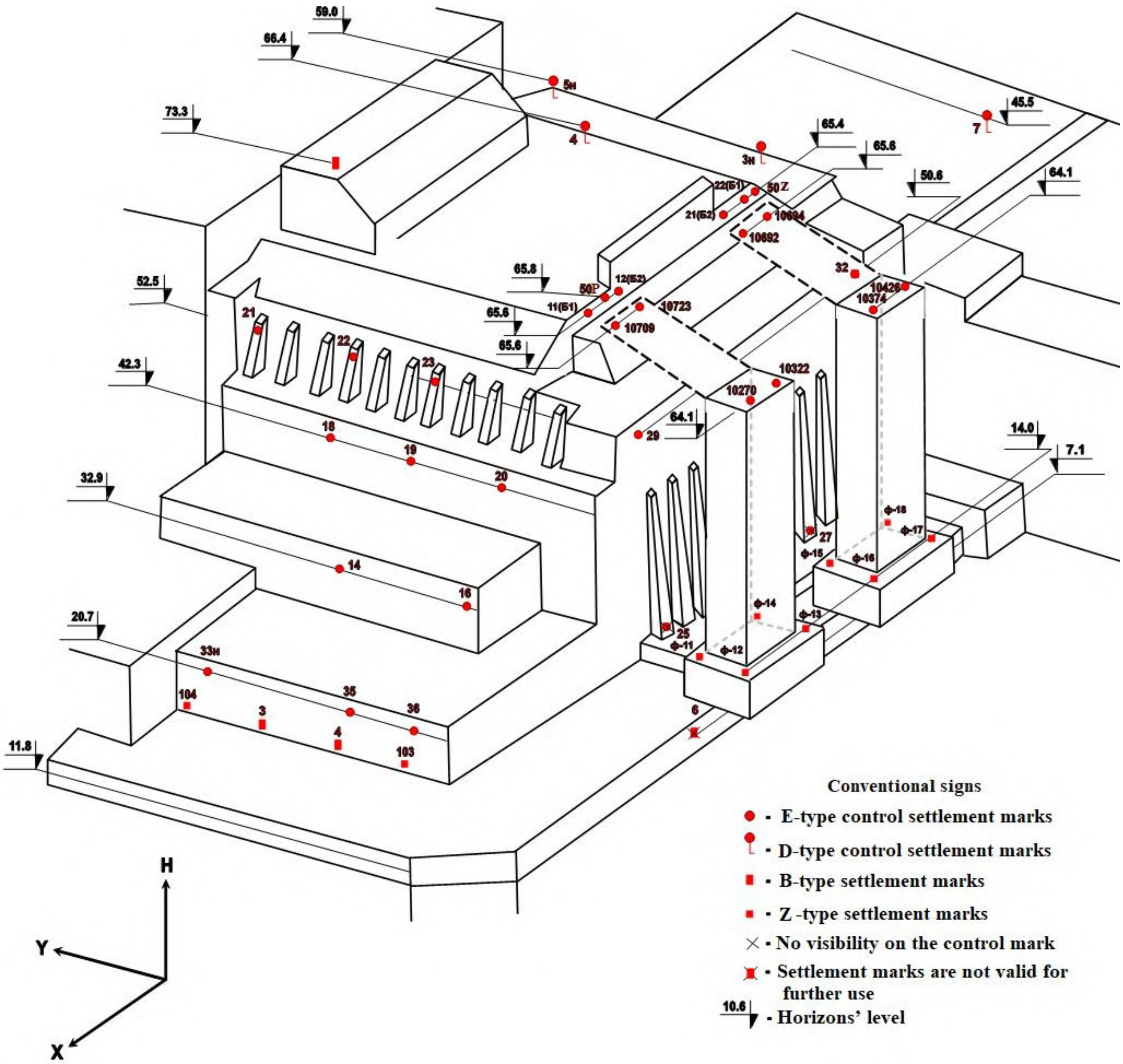

Figure 1. The scheme of the location of control marks at the “Shelter” facility.

The signs installed on the foundations of buildings are placed on the transverse and longitudinal axes of at least four signs around the perimeter. They are installed on the end walls of the “Shelter” facility according to the assembly diagram. In the places of temperature seams on both sides of them, control marks are installed.

When laying sedimentary marks, the conditions of access to them and the possibility of attaching a leveling rail to them should be considered, as a rule, at 0.4–0.8 m from the level of the intersection or the level of the clean floor. Sediment deformation marks should be painted with indelible masking paint, numbered, and tied to the corners of the walls or protrusions according to the scheme [2].

Observations at the points are performed in groups of 4–5 directions to eliminate errors of focus change during one reception of observations due to different distances and errors of closing the horizon. Angular measurements are carried out by high-precision tacheometers [3]. Angles and lines are measured by the method of tunnel triangulation of the 1-T discharge and tunnel trilateration of the 1-T discharge, respectively. The scheme of determining the spatial position of control marks from the points of the plan-altitude network is shown in figures 2 and 3.

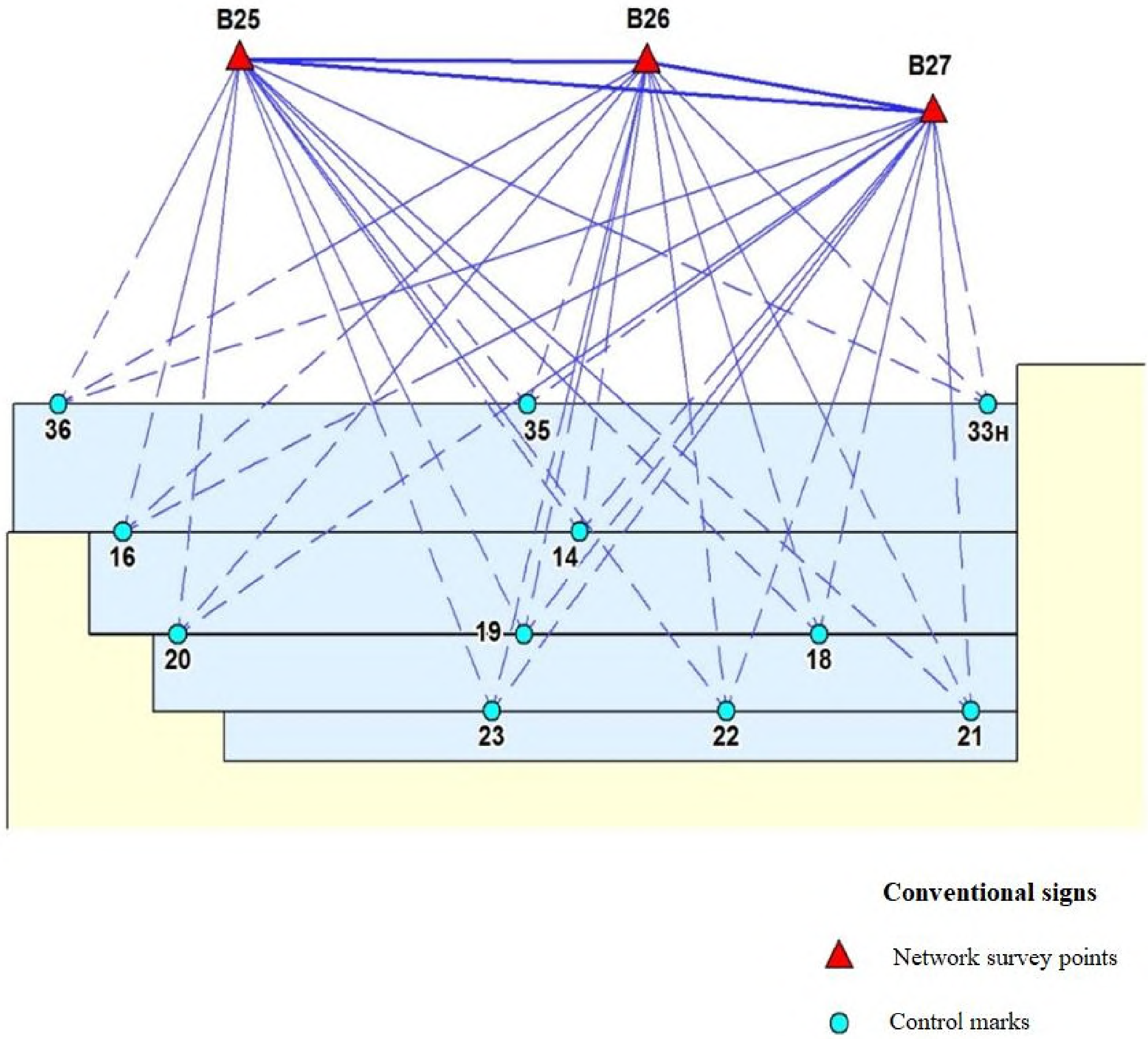

Figure 2. The scheme for determining the spatial position of control marks of the northern cascade wall from the points of the plan-elevation geodetic network at the "Shelter" facility.

Conducting geodetic monitoring by settlement marks requires relevant qualification skills and focus on the process. During the tachymetric survey procedure under the conditions of the increased radiation background, as a rule, two or three surveyors are involved in the work at the same time, which ensures the continuity of the process, since one cycle of observations must be carried out in the same natural and climatic conditions. The obtained survey results are saved on a USB drive in the form of a txt file, which indicates the date of the survey and the object.

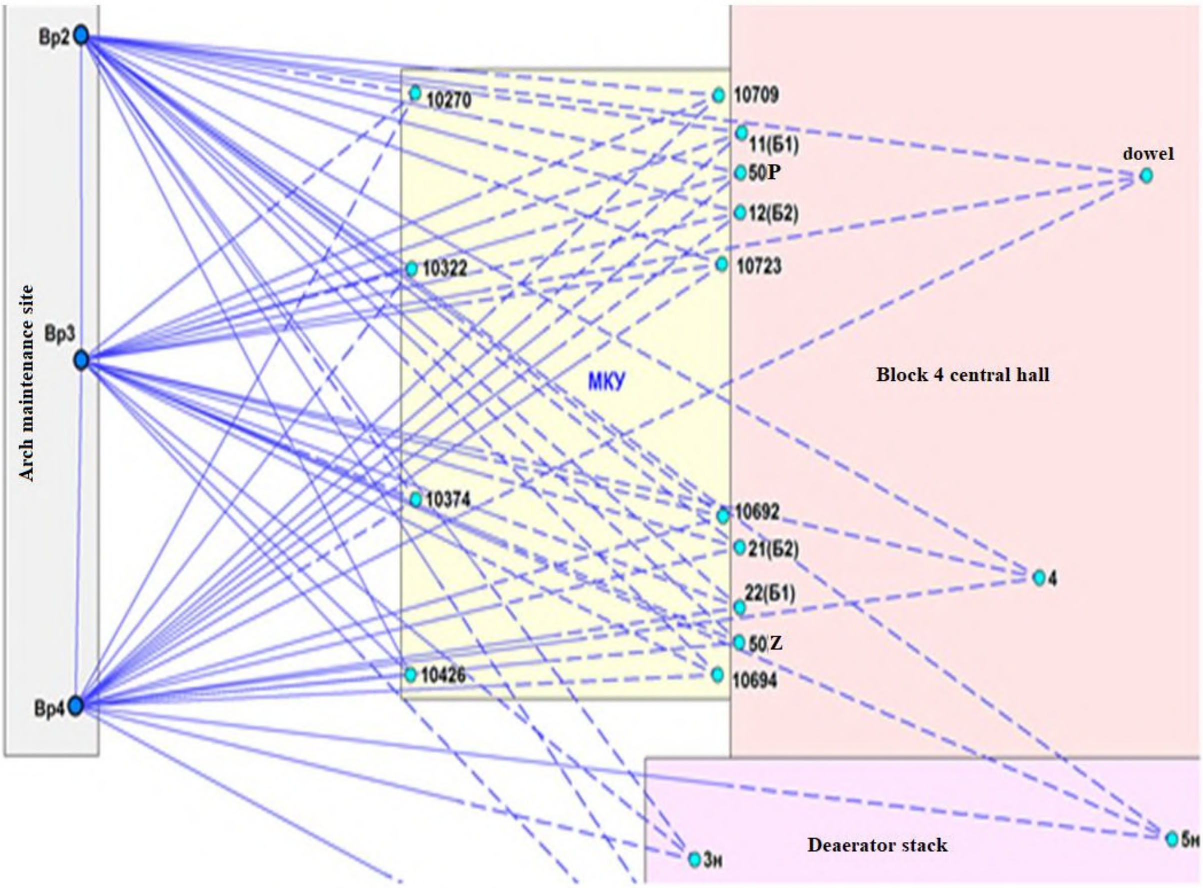

Figure 3. The scheme for determining the coordinates of control marks.

3. Result

Processing of the results is carried out using the CREDO software complex, which allows performing in-camera processing of traditional geodetic measurements and post-processing results of satellite measurements of various accuracy classes in the selected coordinate system with the possibility of considering the geoid model and a complex of reduction corrections. Moreover, various geodetic constructions are performed in the system [4]. The CREDO software product allows importing data from field measurements obtained from electronic tacheometers within accepted formats. After entering the initial data and importing the measurements, the CREDO system automatically recognizes and separates the data by types of measurements and forms the network connections.

The system pre-processes the measurements, calculates, considers the necessary corrections and reductions, and calculates the preliminary coordinates of the points. If necessary, the system allows you to detect, localize and neutralize gross errors in the coordinates and heights of the starting points, linear and angular measurements, and leveling using several methods, including the analysis of the MSE (mean square error) of a unit of weight, automatically in dialog and automatic (tracing) modes by the method of sequential exclusion [5].

The CREDO program analyzes and interprets the results of repeated geodetic measurements during the observation of deformation and sedimentary processes. The program can be used to monitor the condition of buildings and structures, monitor deformation and sedimentary processes, control dangerous areas and solve other local tasks, such as the executive survey of crane tracks, calculation of the deformation of tower-type structures, etc. It is possible to work with graphical data on a plane (2D) and view the deformation surface in a 3D format, both in a static mode and in the dynamics of changes according to the observation cycles [6].

The export of digital models of the terrain, situation, and project solutions made in CREDO systems is implemented in DXF (AutoCAD), MIF / MID (MapInfo), and TXF / SXF (Panorama) format files. At the same time, information about point marks, as well as point, linear, and planar thematic objects is transmitted [7].

After the obtained results of the sediment marks survey, the exported file is uploaded to the CREDO program. As a result, an array of directed vectors to the corresponding points with starting points and names of observation points is obtained (figure 4).

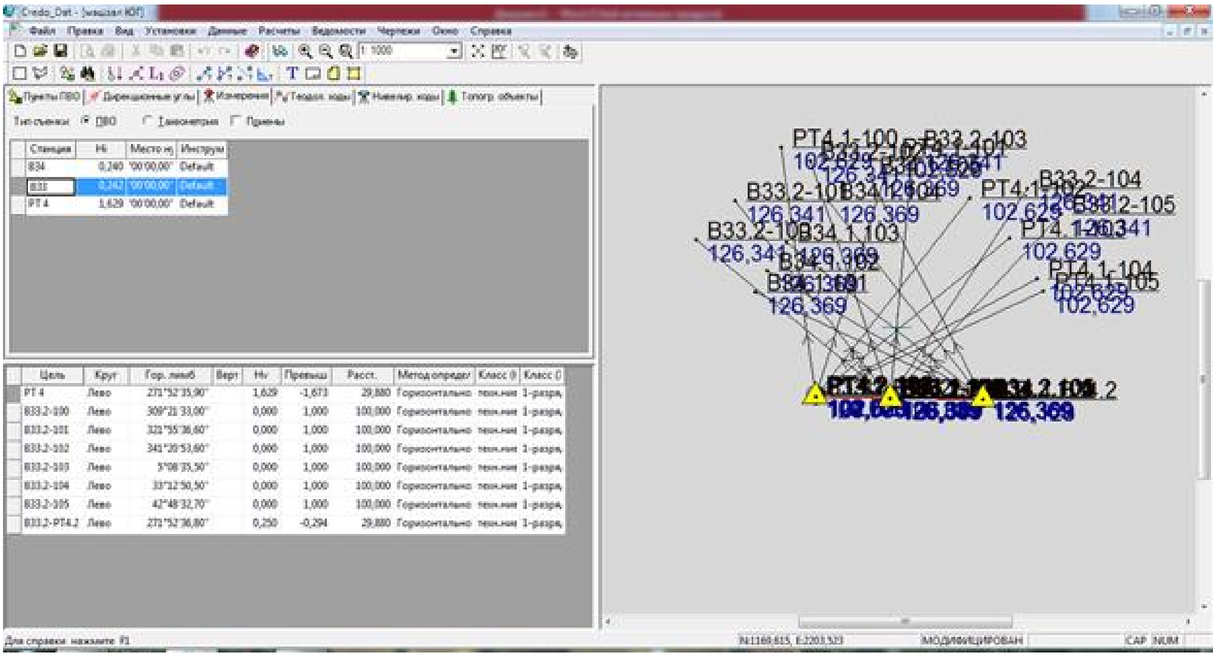

Figure 4. Data processing in the CREDO program.

Next, the file is exported to the AutoCAD software package, where a vector display of the directions of the monitoring points is obtained (figure 5).

Vector directions intersect to form a triangle of measurement error from different survey points (minimum three) under the same observation conditions. At the intersection point of the medians is the center of the observation point (figure 6), where the coordinates of the X and Y point are determined (figure 8). Then the obtained results are entered into the table of observations according to the cycle the geodetic monitoring was carried out.

Since the beginning of the observations, the horizontal movements of 10 control marks of the northern wall of the "Shelter" facility amount to 28 mm on average with the northern direction of the vector. The mark M-18 (figure 8) has the maximum horizontal movements – 34 mm from the beginning of observations.

The average horizontal movements of the control marks (M-16, M-20) of the northwest corner from the beginning of observations are 31 mm with the northern direction of the vector. At the same time, the maximum values of horizontal movements are 33 mm (the M-16 mark).

The average horizontal movements of control marks M-4 and the "Pin" of the roof of the central hall from the beginning of observations is 19 mm with the northern direction of the vector. The maximum values of horizontal movements are 24 mm (for the M-4 mark).

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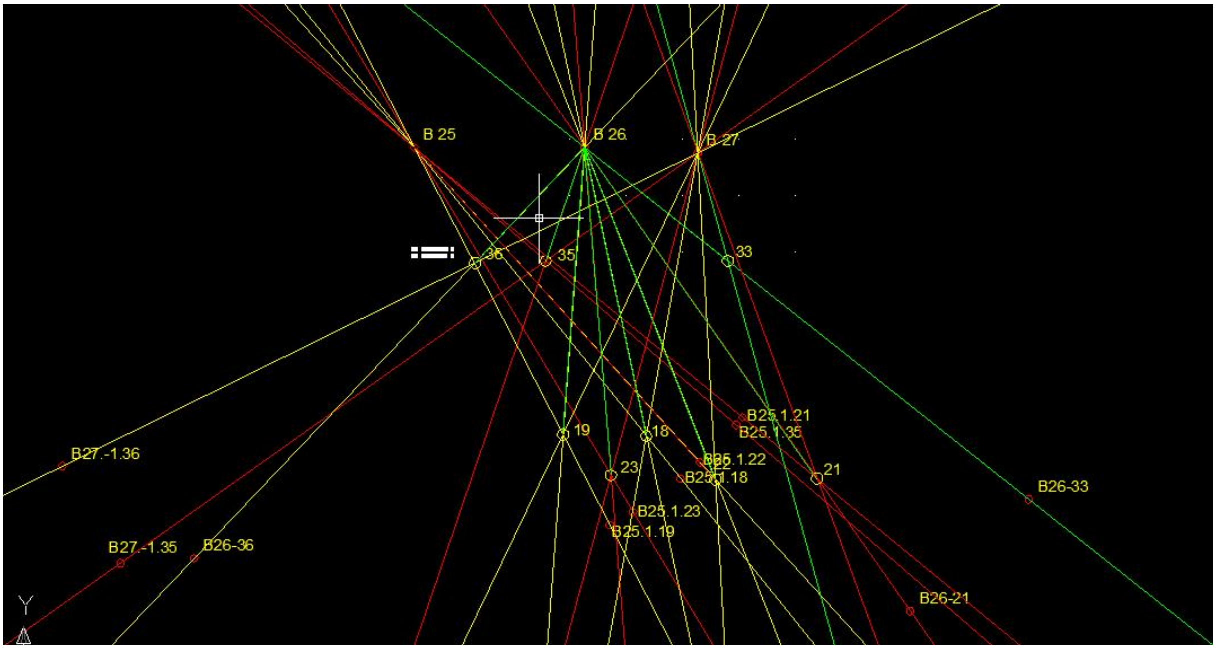

Figure 5. A vector display of directions of monitoring points.

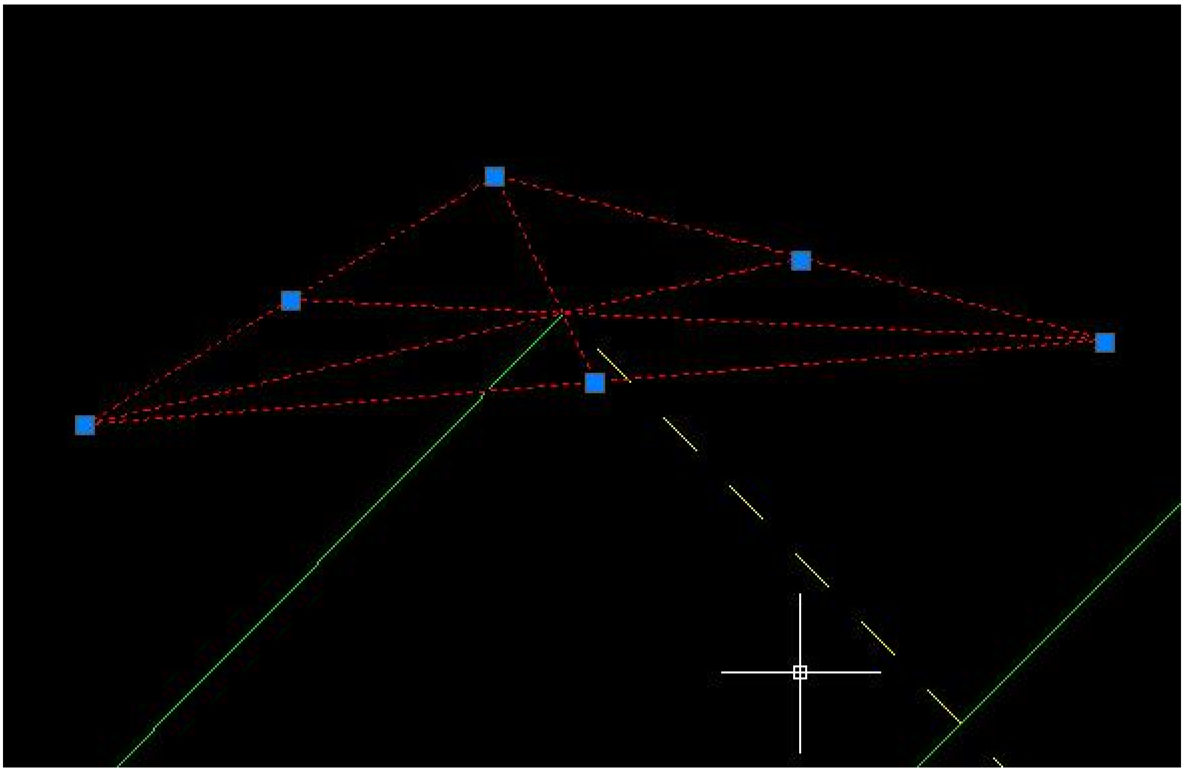

Figure 6. An error triangle, the center of the observation point.

The control marks of the MKU tower along the Z row received average horizontal movements from the beginning of observations – 8 mm with the north-west direction of the vector, and the marks of the P row got respectively 9 mm with the west direction of the vector. The control

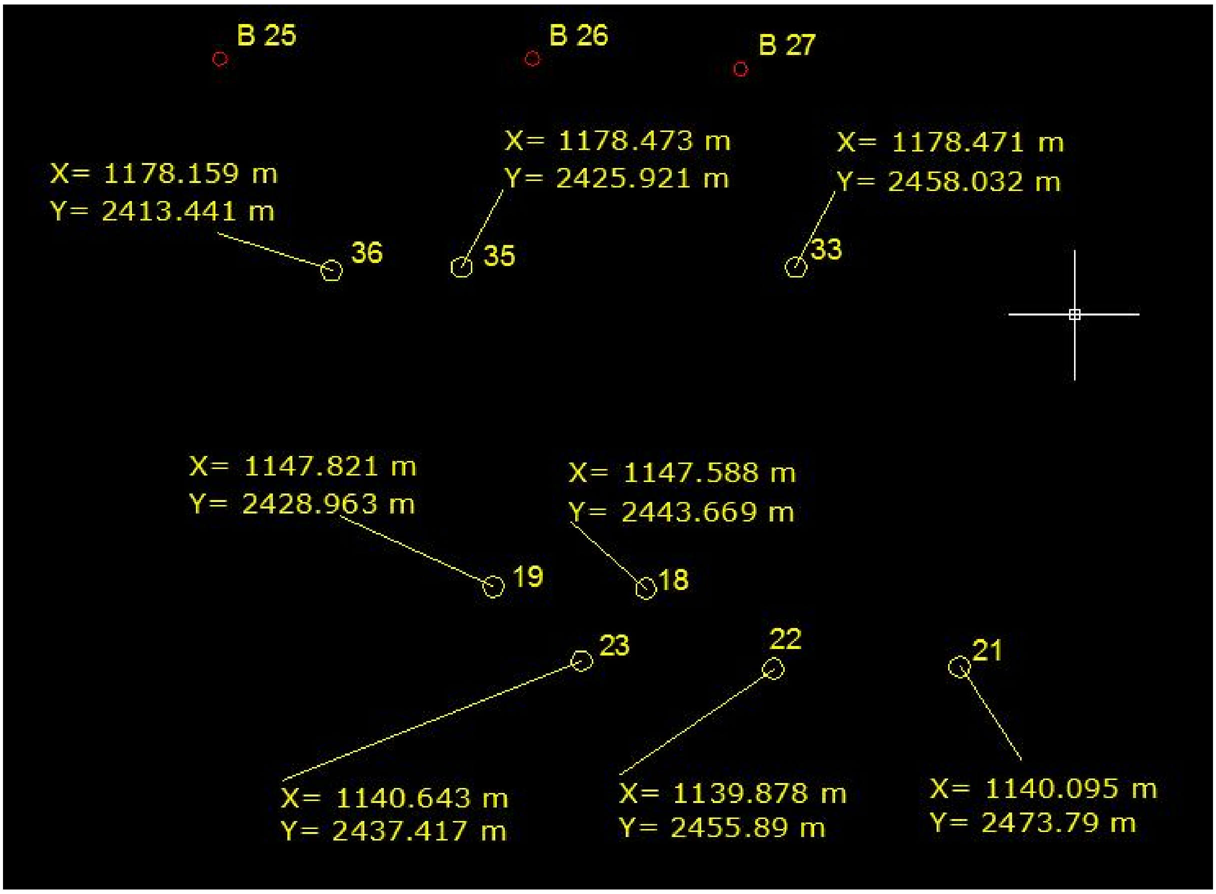

Figure 7. Determined point coordinates.

marks of beams B1 and B2 in rows Z and P received average horizontal movements of 5 mm and 7 mm from the beginning of observations.

Control marks M-50Z and M-50P on the wall axis 50 have received horizontal displacements of 5 mm and 13 mm from the initial observation. The horizontal displacement of the new control marks on the southern wall of the machine hall in row A, from mark M-302 to M-312, during the observation period ranges from 2 mm to 10 mm. The horizontal displacement of the control mark on the western wall of the machine hall on axis 68, mark M-301, has become 6mm since the beginning of the observation.

Analysis of the magnitudes of horizontal and vertical displacements of control marks indicates that the process of deformation is taking place in the object and adjacent buildings and structures.

4. Conclusion

The analysis of the horizontal and vertical movements of the control marks shows that the deformation process of the "Shelter" object and its adjacent buildings and structures continues.

For the analysis of movements of control marks "over a year", operational limits of safe operation are established, since geodetic measurements are equalized between observation same seasons "over a year" with minor fluctuations in measurement temperatures. The obtained results will be used as input data for tracking the dynamics of movements, the stability of building structures and taking timely measures to prevent the destruction of structures, and forecasting emergencies of the "Shelter" facility, as well as its adjacent buildings and structures.

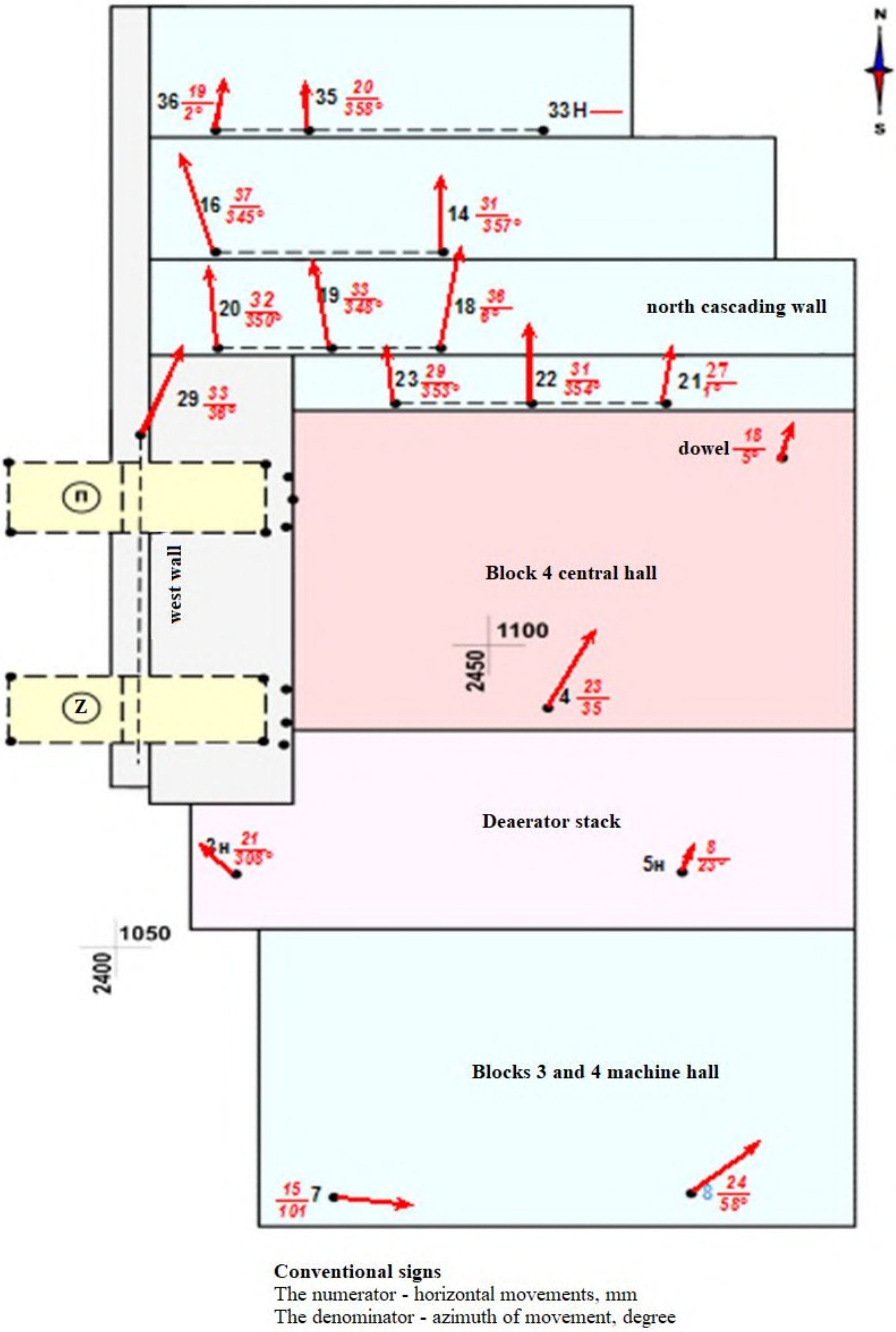

Figure 8. The values of horizontal and vertical movements of control marks of the "Shelter" object.

The values of movements of the control marks of the structures of the northern cascade wall for the annual period, between the seasonal observations of the same name, do not exceed the permissible parameters of movements established by regulatory documents.

The use of GIS technologies allows for fast data processing, reduces the workload on the employee, and makes it impossible to make mistakes during data processing and analysis. With the help of the CREDO software complex, the processing of the results of geodetic surveying of monitoring points reduces the time burden, which allows for a more in-depth analysis of deformation processes, which, in turn, makes it possible to timely identify critical indicators, if any, during data analysis.

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References

[1] State enterprise “Scientific and research institute of construction production” 2009 DBN A.3.2-2-2009 System of occupational safety standards. Occupational safety and industrial safety in construction URL https://e-construction.gov.ua/laws_detail/3074220455066862610?doc_type=2
[2] Tekhnichnyi komitet standartyzatsii “Systemy upravlinnia yakistiu” (TK 189) 2019 DSTU ISO 10005:2019 Upravlinnia yakistiu. Nastanovy shchodo prohram yakosti (ISO 10005:2018, IDT) URL http://online.budstandart.com/ua/catalog/doc-page.html?id_doc=87682
[3] Chen F, Zhou W, Chen C and Ma P 2019 *Remote Sensing* **11**(22) 2623 ISSN 2072-4292 URL https://doi.org/10.3390/rs11222623
[4] Mohylnyy S, Sholomytskyy A, Shmohun E and Pryharov V 2010 Automated system of geodetic monitoring *Suchasni dosyahnennya heodezychnoyi nauky ta vyrobnytstva* vol 1 (Lviv: Vyd-vo Nats. un-tu Lvivska politekhnika) pp 193–197
[5] Dvulit P, Dvulit Z P and Sidorov I S 2019 *Geodesy, Cartography and Aeral Photography* **89** 12–19 URL https://doi.org/10.23939/istcgcap2019.01.012
[6] Chen F, Xu H, Zhou W, Zheng W, Deng Y and Parcharidis I 2021 *GIScience & Remote Sensing* **58**(2) 217–234 URL https://doi.org/10.1080/15481603.2020.1871188
[7] Khainus D, Anopriienko T, Sopov D, Iukhno A and Savchenko M 2022 Perspectives of three-dimensional modelling of geodetic surveys in the assessment of real estate *International Conference of Young Professionals “GeoTerrace-2022”* vol 2022 (European Association of Geoscientists and Engineers) pp 1–5 ISSN 2214-4609 URL https://doi.org/10.3997/2214-4609.2022590047

PAPER • OPEN ACCESS

Geographical foundations of the sustainable development concept: the paradigmatic level

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Geographical foundations of the sustainable development concept: the paradigmatic level

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Abstract. A constructive solution to the global environmental problem is possible within the framework of the information-space-time paradigm, the main of which is a constant (in terms of the main laws of conservation) amount of information, space and time, and thus deriving equivalent interchangeable units of their measurement. The methodological uncertainty of the very idea of sustainable development prompts the interpretation of this idea precisely taking into account the geographical picture of the world in the context of the informational-spatial-time paradigm.

1. Introduction

During the 30 years of existence of the sustainable development concept (SDC), the global environmental problem, the solution of which it was aimed at, has not been solved, but continues to worsen. Such aggravation forces scientists to revise the methodological guidelines for the development of the subjects of their sciences [1, 2].

Geography has certain advantages compared to other sciences in the correctness of the formulation and subsequent solution of the global environmental problem, on which the complex interrelationships of Nature-Population-Economy are closed [3, 4]. The correct formulation and justification of real ways of solving the global environmental problem is a unique chance for geography to strengthen its fundamental theoretical and methodological positions in the system of sciences and strengthen its applied status [5].

Ukraine's modern progress towards a "post-industrial", "informational", "globalized" society under the banner of the concept of sustainable development, the methodological guidelines of which have not yet been definitively determined, and therefore are rather dubious, forces us to think about the more general principles of human, regional, and national development – development, which determines the social demand for the formation of certain paradigms of scientific research [6, 7].

For a long time, geography has been dominated by the spatial paradigm, which in modern conditions requires further in-depth development and improvement in accordance with the requirements of the time. The scientific community is only beginning to realize the connection between the correct formulation of many global problems, primarily ecological, and the use of geographical space by Man. Most likely, the correct formulation of the ecological problem with the aim of its further solution lies in the optimization of the geographical space – optimization that can be carried out only by researching modern trends in the development of spatial socio-natural systems – Important objects of geographical science.

In fact, the global environmental problem, embodied in the concept of sustainable development, has all the signs of interdisciplinary nature and fundamentally cannot be solved in the realm of only geographical paradigms [8, 9]. The study of the general scientific origins of the global environmental problem allowed the authors to choose an integrative direction for its solution, as well as to consider the typological principles of the formation of spatial socio-natural systems, within which it should be solved as soon as possible.

2. Research methodology and methods

The concept of noosphere genesis, the geographical roots of which are interpreted in the geographical theory of noosphere genesis and in the geographical picture of the world [10], lies in the field of correct formulation of the global ecological problem. The essence of the geographical theory of noosphere genesis lies in a completely different interpretation of the civilizational development of mankind, considered from the standpoint of ecosystemology [11]. The primary spatial unit of noosphere genesis is not a civilization, but a modified human ecosystem, or an agroecosystem, the evolution of which leads to the formation of other noospheric ecosystems – urboecosystems and infraecosystems [10]. In the process of noosphere genesis, a person modifies trophic relations in a natural ecosystem primarily due to a conscious change in its edaphic (spatial) component. This happens due to the formation of "traps" for time, space and information [10]. As a result, an agroecosystem is formed in which spatial relations have changed. But such a change does not make the modified ecosystem of Man less "natural". The synthetic nature of the global environmental problem is manifested in specific relationships, the symbiosis of which ensures its correct formulation. In particular, geography provides awareness of spatial relations, ecology – trophic, history – evolutionary, philosophy – cognitive.

The basis of the author's ideas about the geographical content of the global environmental problem is that when any phenomenon (body, process) develops (moves), it necessarily leaves behind a projection of this movement in a dimension one unit higher than the previous one. Thus, the movement (development) of any material body in the direction of a higher dimension gives this body emergent (qualitatively new) properties. If the above approach is applied to spatial phenomena, when projecting (superimposing) any two-dimensional bodies, one should expect the formation in the "fourth dimension" of some qualitatively new spatial formation. But this statement is valid only for such objects, the proof of the objective existence of which is already feasible and a recognized fact – landscape complexes, ecosystems, agricultural areas, types of land use, types of agricultural territory organization [12].

The ecological (geo-ecological) content of noosphere genesis today is not in doubt among almost anyone, primarily because the spatial boundaries of landscapes and ecosystems have almost been equated [13]. It is from this that the conclusion is drawn that the unifying beginning for the development of socio-natural (noospheric) laws is the territory. At the same time, such a unity does not exclude the formation of their divergent borders in a two-dimensional sense, and, therefore, involves the search for the mechanism of their formation in such a "nature-society" dichotomy, where society is the "Homo Sapiens population" [14].

The general concept of the agroecosystem, or Homo Sapiens ecosystem, was developed in previous works. An agroecosystem is an ecosystem that combines the anthropic and social nature of man [15]. Awareness of the spatial essence of such ecosystems lies within the scope of the subject of geographical sciences and is closest to the content of socio-natural systems. Such a view is also correct because it does not differ from the main position of ecosystemology [11] and gives the right to include a person in biocenotic ecological niches, in which food relations include humanity. However, the role of inanimate (dead according to Vernadskyi) matter in the vital activity of the human population is very special. So, if in other populations this substance does not go beyond the biological limits of the organism, entering it (albeit in transit) as a biochemical component (i.e., included at the organismal level), then the phenomenon of the human population consists in the fact that an inanimate (fossil) substance taken from nature, in its vast majority is deliberately excluded by man from the organismic level and brought to the level of joint consumption by the entire population (figure 1).

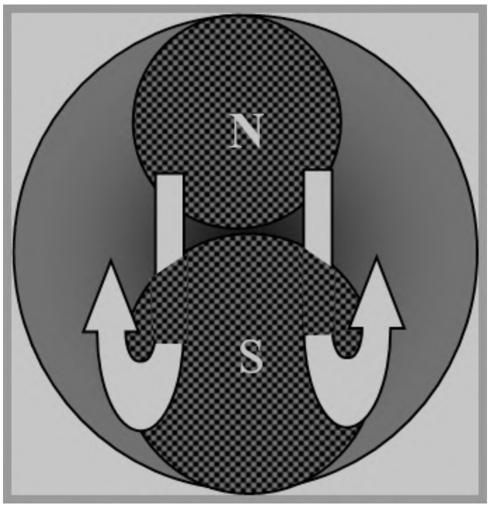

Figure 1. The general direction of the material transformation of the natural environment, which leads to the "compression" of the geographical space (N – nature; S – society).

At the same time, such consumption either does not reach the body, or completely leaves its physiological limits, confirming the purpose of this exchange in only one direction – the extraction of natural inert substance without its return to food chains. It is at this stage that thanks to the technical-cultural-transformative activity of man with the involvement of the inert substance of the biosphere, "materialized information" is formed in the form of "consumer values" [16].

Thus, the transition from the organismic to the population level is conceptually significant in understanding the geoecological essence of the human population. Taking into account the spatio-temporal existence and the total mass of ecological groups of organisms (producers, consumers, reducers) in the biosphere, we concluded that plant species are characterized by a stationary-dispersed type of mediation of geographical space. Animal species and groups (consumers) carry out dynamic and dispersed mediation of geographical space. In contrast to the purely "natural" ones, the human population has a dynamic-continuous type of mediation of geographical space, which is carried out in the direction of its constant "compresion" [17] and fundamental energy-material-informational transformation. At the same time, if in natural geobiocenoses such information exchange is aimed at improving the competitive struggle for the environment (while not going beyond the boundaries of the ecotope), then the human population long ago won this competitive struggle with other species and conducts it within its own population, thereby reaching ecosystem level of organization of living matter. Therefore, the "ecotope" of Homo Sapiens in the classical sense of this term goes beyond the organismic level of the organization of the species and includes the population and even the ecosystem level. Thus, it is more logical to talk about an ecological niche with vaguely defined spatial boundaries. Considering the spatial behavior of Man as the search and subsequent transformation of his ecological niche in the process of noosphere genesis, the spatial dynamics of the Homo Sapiens population was investigated in historical retrospect [18].

3. Research results

As a result of the existing spatial dynamics of Homo Sapiens, the information influence of urboecosystems (hinterlands) on the surrounding space is gradually increasing thanks to the means and tools of the information infrastructure [19], which is where the name "infraecosystems" actually comes from. At the same time, the highest level of information influence, which leads to an increase in planetary entropy, is characteristic of today's so-called "world cities" [20]. This influence is manifested in the diversification and inversion of the geographical space by world cities, studied in previous publications [10, 16]. According to the results of the author's research, the territories that fall into the hinterlands of neighboring "world" or the highest ranked "central" places are forcibly transformed by them into service, or into infrastructure [10]. From this, an important methodological conclusion is drawn, that in W. Chrystaller's theory, central places have always performed not serving, but diversifying functions, redistributing the geographical space to their advantage.

Research in previous publications of the ontological content of the space of time and information made it possible to build a methodological scheme of the interconnection of agro-, urban- and infra-ecosystems (figure 2).

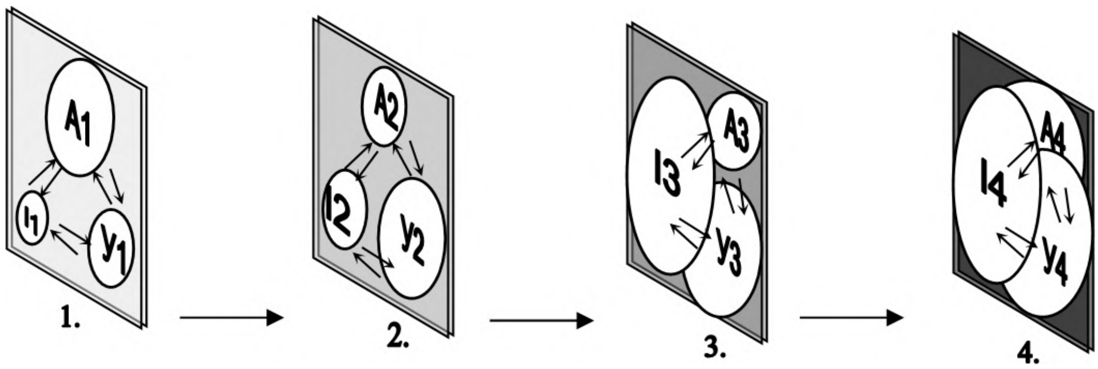

Figure 2. The system of relations in the modified ecosystem of Homo Sapiens and its development over time. Agroecosystems (A) – urban ecosystems, (Y) – infraecosystems (I).

At the early stages of the formation of the modified human ecosystem (agroecosystem), the greatest attention was paid to the actual "food extraction" (figure 2.1). At the same time, information connections between different ecosystems were embodied in the primitive cults of paganism, primarily due to the lack of study of nature and the blind worship of its individual material components. At the same stage, urbo-ecosystems were just beginning to be born (recruitment of the supreme power, priests, and troops into stationary settlements). The degree of compression of the geographical space is the lowest.

At the second stage (figure 2.2) as a result of the Neolithic revolution, which is also called the "axial time" (with the beginning of the process of noosphere genesis), the informational component of this process in the form of the main world religions began to relentlessly and predestinedly form infraecosystems by introducing a spiritual beginning into international spatial relations. Cities (urboecosystems) become the main centers of such informational influence, around which hinterlands are gradually formed, which leads to a gradual "compression" of geographical space.

The third stage – modern – is associated with the acquisition of the highest level of information density by urban ecosystems and the transformation of some of them (world cities) into infraecosystems (figure 2.3). At the same time, global entropy acquires the highest degree, the result of which is the greatest "compression" of geographical space due to the growth of its material filling.

At the fourth stage (figure 2.4), the most developed infraecosystems "pull up" other types of noospheric ecosystems to their level. All three types of ecosystems will grow spatially due to the increase in interdependence, which will lead to the maximum compression of geographical space and the maximum growth of global entropy. According to the author's concept of border conflicts, the next stage of the formation of the modified ecosystem of Man is now beginning – the cosmic one, when cosmoecosystems are already beginning to form [21].

The deepening of general scientific ideas about the role of geographical space as a carrier of physical interactions, gravity, landscape and morphogenesis, the process of interaction between nature and society, modern globalization and post-industrialism, and many other things that are carried out in Nature and perceived by Man, encourage the construction of a proper geographical picture of the world [10].

The existing space-time paradigm of geography – an idea about the participation of the category of time in the development of the geographical process – is developed in a number of works. Just as the classical spatial paradigm (Kant-Ritter-Hettner) was focused on the selection of geocomplexes and geosystems according to their spatial form and territorial structure, the new paradigm is focused on the selection of geographic complexes and systems according to their functioning and vital activity, on the analysis of life cycles of geographic complexes of various types and scales.

For our study, the idea of time as an integral attribute of the process of interaction between nature and society plays a special role, since this process is inextricably linked with the space that life fills as a result of noosphere genesis. In our case, the process of interaction between nature and society (movement) in planetary space-time is considered. It is imagined in the form of its two main components – nature and society. Together, they actively fill the geographical space since the Neolithic, which gradually leads to its compression [10]. Considering the process of noosphere genesis as one that is formed in a certain frame of reference, it is concluded that the compression of geographical space must be compensated by real time. For such compensation, a person creates "time traps" as if putting it off "for later". To a certain extent, humanity has "borrowed" time from nature, by which it is "ahead" of it in the process of its development.

Thus, the main cause of the environmental problem lies in the different rates of development of nature and society. The result of this difference is necessarily "postponed" in geographical space. For a constructive solution to the "global ecological problem", it is necessary to find such areas of space, in which the difference in the speed of nature and society is reflected, and in the future, gradually reducing them, bring them to optimal ratios.

In the future, according to logic, in addition to the real territory, it is necessary to find those "segments" of time that are "borrowed" and that are reflected in space. In order to search for "negative" segments of space, the spatial dynamics of agroecosystems formed on the territory of the Kharkiv region were investigated (figure 3). The study of agroecosystems made it possible to draw a conclusion about the simultaneous existence of two types of borders, the dynamics of which go beyond the limits of two-dimensional understanding. According to modern ideas, such "non-coincidence" leads to an increase in the level of planetary entropy [10], and, therefore, to informational "tension", which, most likely, is the cause of the emergence of not only environmental, but also many other global problems. The above analysis was carried out in the context of the modern space-time paradigm. The absence of an interpretation of the category of information (entropy/negentropy) explains, in the opinion of the author, the impossibility of correctly posing the environmental problem.

It is from this antithesis that the general logic and stage sequence of the development of the new – information-space-time paradigm, reflected in the diagram (figure 4), originates. In this

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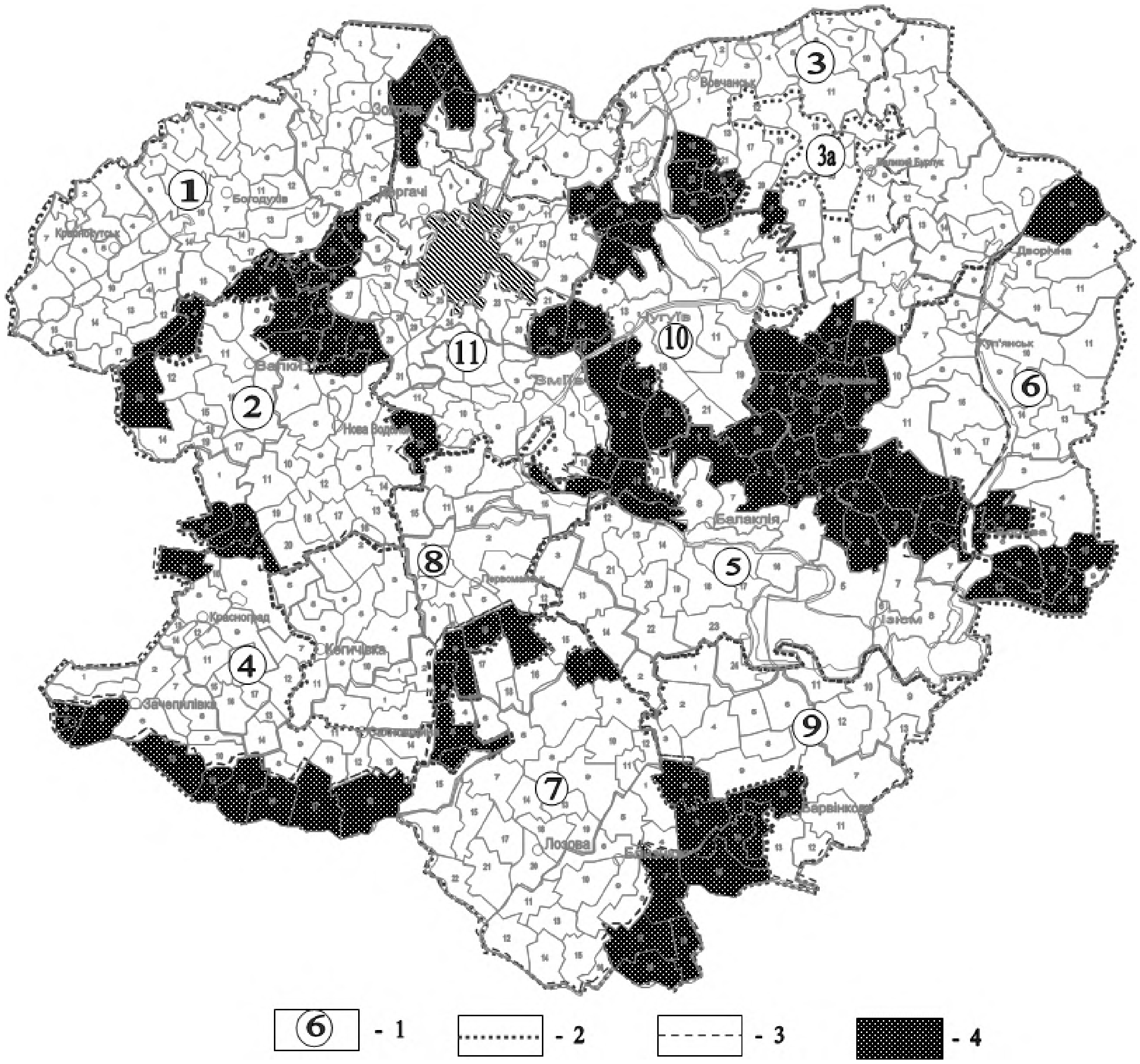

Figure 3. Spatial "mismatch" of agroecosystem boundaries. Explanation of symbols: 1. Numbers of agricultural districts; 2. Boundaries of agricultural districts (economic boundaries of agroecosystems); 3. Boundaries of type of territory organization (natural boundaries of agroecosystems); 4. Areas (segments) of space, on which natural and economic boundaries do not "coincide".

scheme, each of the blocks (stages) that reflect the development of the specified paradigm is a cybernetic system with feedback, where the most contradictory theses that were put forward during the research act as a regulator (R). The horizontal directions of the table reflect the logic of the formation of scientific knowledge from the extraction of empirical facts to the construction of a new theory, and on its basis – a scientific picture of the world. The process of scientific research logically ends with the practical implementation of the results of theoretical research.

At the same time, the main features of the new information-space-time paradigm should be:

1. Genetic unity of space, time and information in the interpretation, description and modeling of geographical process.
2. Equal "participation" of space-time and information in the ontological content of the information-space-time paradigm, which implies the same equal "inclusion" of them by

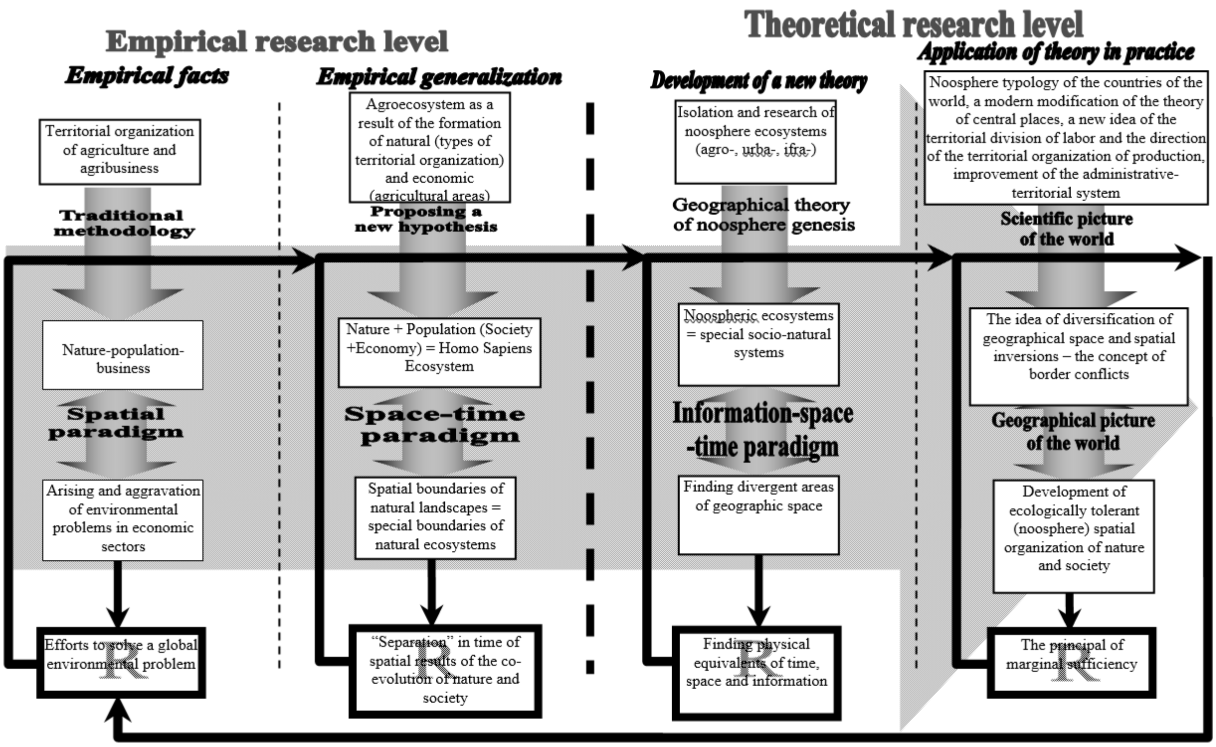

Figure 4. Development of information-space-time paradigm.

geographers and philosophers in the corresponding types of models, classifications and typologies.

3. A constant (in accordance with the main laws of preservation) amount of information, space and time in the areas of development of the geographical process in the entire oecumene.
4. A close cause-and-effect relationship between the qualitative structure of information, time and space and the level of planetary entropy.
5. The presence of invariant information, space and time, consistent with the logic of the process of noosphere genesis.
6. Closeness of the development of ideal models of space use to calculations of world constants.
7. The possibility of deriving equivalent interchangeable units of measurement of space and time information.

Based on the above signs of the new information-space-time paradigm, it is necessary to consider several examples of "deviation" of the development of its information component from the invariant. Thus, in the modified ecosystem of Homo Sapiens, trophic relations are artificially "stuffed" by humans into "time traps" – grain storage in elevators, meat freezing in refrigerators, preservation of vegetables, fruits, meat, milk, production of concentrated products, which almost do not deteriorate over time. "Traps for space" are manifested at the level of agroecosystems in the organization of crop rotations, fodder arable land [22], contour-ameliorative farming systems, and other types of land use, with the help of which Homo Sapiens artificially regulates trophic relations in its own modified ecosystem. Urboecosystems generally lead to asymmetry of geographical space [19].

In our opinion, similar to "traps" for time and space, there are also "traps for information", skillfully "set" by man in the process of noosphere genesis. A very large-scale "trap for information" is the phenomenon of "stretching" by Man of the single gene pool of cultivated plants (N. Vavilov) in the process of noosphere genesis. The difference from time traps at the organismal level is quite significant, since this process vividly embodies the transformation of geographical space through the spatial destructurization of the ecological niche and time, if we consider the desire to breed new high-yielding varieties as "saving time". It is significant that the share of genetically modified food products has been constantly increasing since the beginning of the noosphere genesis process and, according to modern estimates, almost doubles the area of UK [23]. At the same time, there is an increasing decrease in the resistance of the human population to microbiological disturbances [24]. "Traps for information" are manifested in the economy as well. In particular, the very term "shadow economy" comes from hidden (at least from the payment of taxes) commodity and information flows. As for the production of contraband products under the brand name of well-known brands, this is generally an ideal case of "traps for information". Given that such products are much cheaper than the original, the price difference between them can be the monetary equivalent of "stolen" information. Therefore, searches in the geographical space for informational imprints such as the Retheum sphragides can help in understanding the complex structure of planetary space-time. According to our concept, any socio-natural systems carry and leave complex sphragide information, which actually regulates all spatial relations [10].

4. Conclusions

The basis of the modern informational-space-time paradigm of geography is the following basic theoretical propositions, which should help in the formation of the modern geographical picture of the world:

1. During the evolutionary development of humanity on the planet Earth, significant spatial transformations of its surface took place. The modern stage of these transformations is described by complex information processes, which in turn cause the corresponding energy-matter flows. Thus, modern "globalization" of production and social life is carried out under the slogans of the civilizational process, which seems to be able to lead underdeveloped countries to a better fate.
2. At the same time, with the help of a system of repeaters (urboecosystems), there is a spatial redistribution of various resources in favor of developed countries due to the indirect influence on the resource potential of the planet.
3. "Civilization" and anthropocentrism embedded in this term acquires modern forms of spatial chauvinism, which gives reason to automatically assign individual ethnic groups and even entire countries from the standpoint of "civilization" to "civilized" and "uncivilized", "developed" and "underdeveloped". However, the biosphere role of the Australian aborigines, or the "primitive" naturalized societies of South Asia, is much more positive than that of the superpowers. And even further – there is a desire to distinguish between "higher animals" and "lower animals". However, the role of these "lower animals" in maintaining the stability of the biosphere (reducers) is much more positive than the "higher" ones and, above all, the Homo Sapiens species.
4. The so-called "global environmental problem" is the result of spatial incoherence of territorial combinations of different types of relays – infraecosystems, agroecosystems, urban ecosystems; from here, the search for optimal models of the territorial organization of society is quite logically perceived.
5. Higher "informatization" will imply at some stage the oversaturation (compression) of geographical space with various combinations of "retransmitters", which will lead to qualitatively new shifts in the spatial being of humanity. Most likely, such shifts will lead to the identification of two main directions of information density reduction. The first direction is extensive – artificial stretching of the critical limit of compaction due to the development

and implementation of optimization models of geographic space (W. Christaller, W. Isard, B. Rodoman, O. Topchiiev). The second direction is intensive – the gradual formation of artificial ecosystems (cosmoecosystems) in extraterrestrial space.

6. When implementing an extensive (more realistic) way of further development, one should be guided by the principle of marginal sufficiency, according to which the optimization of the geographical space by humans should take place in the direction of rotation of individual groups of elements of the territorial structure and their functions. In particular, the gradual conscious transformation of urboecosystems into agroecosystems and vice versa (A. Chaianov) while preserving the binding function of infraecosystems.
7. The civilization process is a certain period (qualitatively a new stage) of a much longer-term process, which went back to the “axial time” (K. Jaspers) and which is based on the informational processes of the universe, which were embodied in the birth of the biosphere, its further complication, fundamental its transformation by the species Homo Sapiens due to the spatial re-planning of the flows of matter and energy and the subsequent exit beyond the limits of the terrestrial biosphere into the Cosmos.
8. The biosphere-noosphere theory of V. Vernadsky – is the ultimate ideal model of the development of the biosphere, in the event that Humanity becomes “smarter”. Predecessors of V. Vernadsky in the spatial sciences developed models narrower in scope (J. Thunen, A. Weber, W. Christaller). The development of such models relates the mentioned studies to the finding of world constants (absolute zero, acceleration of free fall, speed of light, etc.), but in our case these constants are spatial.
9. The development of ideal models of spatial organization may continue in the search for spatial equivalents of time, energy, and information, based even on the existing laws of conservation. Based on the assumption that the amount of planetary space is constant (invariant), it is possible to search for excess or negative segments of space that arise in the process of noosphere genesis as a result of the formation of “time traps” and “information traps”. Thus, it becomes possible to calculate the corresponding coefficients of “exceeding” the invariant due to going beyond its limits. Most likely, the highest coefficient of space consumption (spatial entropy) will be developed countries that most actively structure it.
10. The system of spirituals and ethical values of humanity should be based on the principles of observing biosphere interests, which requires a deep understanding of one’s place (humanity), and therefore participation in biosphere processes. Instead, humanity should not separate itself within the framework of “globalist”, “post-industrial”, “civilizational” concepts from the process taking place in the biosphere of its evolutionary development. When developing development programs at the national level, it is necessary to take into account global trends in the structuring of geographical space with the subsequent “search” of one’s place in the process. This forces us to look for other perspectives of Ukraine’s “entry” into the “post-industrial” society.

Developing a geographical world picture in the context of the information-space-time paradigm allows for the modification of the main theoretical foundations of modern geography, as well as a new look at the structuring and awareness of the global environmental problem. “Hopelessness” in its solution comes from an incorrect definition of methodological guidelines in the study of the main foundations of the interaction of nature and society, and a derived from this erroneous understanding of the phrase “sustainable development”. The methodological uncertainty of the very idea of sustainable development prompts the interpretation of this idea precisely taking into account the geographical picture of the world in the context of the information-space-time paradigm.

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References

[1] Caiado R G G, de Freitas Dias R, Mattos L V, Quelhas O L G and Leal Filho W 2017 *Journal of Cleaner Production* **165** 890–904 ISSN 0959-6526 URL https://doi.org/10.1016/j.jclepro.2017.07.166
[2] Levcheniuk E, Vlasenko F, Tovmash D and Rykhlitska O 2020 *Journal of Geology, Geography and Geoecology* **29**(4) 745–754 URL https://doi.org/10.15421/112067
[3] Chernov B and Dudka I 2021 *Journal of Geology, Geography and Geoecology* **30**(3) 407–420 URL https://doi.org/10.15421/112137
[4] Pylypenko S and Ivashchenko O 2022 *Philosophy and Cosmology* **28** 22–31 URL https://doi.org/10.29202/phil-cosm/28/2
[5] Topchiyev O G 2022 *Ukrainian Geographical Journal* (3) 3–12 URL https://doi.org/10.15407/ugz2022.03.003
[6] Prybytkova I 2019 *Visnyk of V. N. Karazin Kharkiv National University. Series "Sociological studies of contemporary society: methodology, theory, methods"* **42** 51–58 URL https://doi.org/10.26565/2227-6521-2019-42-05
[7] Boichenko M I 2021 *Anthropological Measurements of Philosophical Research* (19) 15–22 URL https://doi.org/10.15802/ampr.v0i19.235956
[8] Hickel J 2020 *Ecological Economics* **167** 106331 URL https://doi.org/10.1016/j.ecolecon.2019.05.011
[9] Shindaulova R 2022 *Philosophy and Cosmology* **28** 107–117 URL https://doi.org/10.29202/phil-cosm/28/9
[10] Sonko S 2019 *Philosophy and Cosmology* **22** 51–74 URL https://doi.org/10.29202/phil-cosm/22/5
[11] Holubets M 2000 *Ecosystemology* (Lviv: Polli)
[12] Andreichenko A, Andreichenko S and Smentyna N 2021 *Philosophy and Cosmology* **26** 46–61 URL https://doi.org/10.29202/phil-cosm/26/4
[13] Denysyk H, Chyzh O and Kanskyi V 2022 *Landscape Science* **1** 5–17
[14] Dronova O and Nahornyi T 2021 *Ukrainian Geographical Journal* (2) 20–30 URL https://doi.org/10.15407/ugz2021.02.020
[15] Hudzevich A, Nikitchenko L, Baiurko N, Hudzevich L, Frytsiuk V and Levchuk N 2020 *Journal of Geology, Geography and Geoecology* **29**(3) 520–529 URL https://doi.org/10.15421/112047
[16] Sonko S, Maksymenko N, Vasylenko O, Chornomorets V and Koval I 2021 *E3S Web of Conferences* **255** 01046 URL https://doi.org/10.1051/e3sconf/202125501046
[17] Puhach S 2019 *Ekonomichna ta Sotsialna Geografiya* **82** 27–33 URL http://bulletin-esgeograph.org.ua/images/docs/Volume-82/Puhach_27-33.htm
[18] Masikevych Y, Shestopalov O, Nehadailo A *et al.* 2015 *Theory of Systems in Ecology* (Sumy: Sumy State University)
[19] Petrykivska O 2021 *Philosophy and Cosmology* **27** 135–144 URL https://doi.org/10.29202/phil-cosm/27/10
[20] Husieva N V, Kucheriava G O and Suptelo O S 2018 *Visnyk of V. N. Karazin Kharkiv National University, series "Geology. Geography. Ecology"* (47) 91–100
[21] Soroka L 2020 *Philosophy and Cosmology* **25** 43–56 URL https://doi.org/10.29202/phil-cosm/25/4
[22] Boyko A L, Sus N P, Boyko O A and Orlovskyi A V 2020 *Agricultural Science and Practice* **7**(2) 35–43 URL https://doi.org/10.15407/agrisp7.02.035
[23] 2022 ISAAA in 2021: From Partnerships to Public Trust URL https://www.isaaa.org/resources/publications/annualreport/2021/pdf/ISAAA-2021-Accomplishment-Report.pdf
[24] Radchenko M, Ponomareva I, Pozynych I and Morderer Y 2021 *Agricultural Science and Practice* **8**(3) 50–70 URL https://doi.org/10.15407/agrisp8.03.050

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Optimized fuel values for emission reduction

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Optimized fuel values for emission reduction

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Abstract. Aviation is an integral and vital part of modern society. The growth over the last decades has consequences for greenhouse gas emissions and reducing this through efficiency within the same framework is difficult. Precision flight planning is crucial for reliably and optimized real environment aircraft operation. The presented study gives an overview of the status of the legal requirements for flight planning under the current fuel requirements of the European Union Aviation Safety Agency (EASA) and the emerging opportunities for fuel savings. As part of the larger study, planned and actual fuel figures of an international cargo airline were statistically analyzed. The overall analysis showed that there was no significant deviation between planned and consumed fuel. Based on the results, an adjustment of the planned alternative fuel quantity can be considered within the framework of an individual fuel plan. The possible savings potential using the example of Destination Alternate Airport fuel is presented.

1. Introduction

In the 100 or so years since the first powered flight, the aviation industry has experienced rapid growth [1]. Fuel needed to operate thousands of flights worldwide every day is one of the most important cost factors in the airlines' business. According to the International Air Transport Association (IATA) report on the economic performance of the airline industry, global fuel costs were predicted to be \$206 billion in 2019, later estimated to be around \$188 billion in the 2019 end-of-year report. For 2020, the same report predicted fuel costs to fall to \$182 billion, equivalent to 22.1% of average operating costs [2]. Figure 1 shows a corresponding chart by Airbus [3].

Aviation emissions have a climate impact, which came more and more into focus. In 2020 almost every commercially used aircraft still has a propulsion system based on fossil fuels. Emissions from aircraft are greenhouse gases and noise. Fuel costs are therefor not the only driver for reducing the amount of fuel consumed. In recent years, the impact on the environment has become more and more important. The high traffic volume is associated with an enormous demand for aviation fuel and the associated high emissions on the other side. Lee et al. provide an overview of CO_2 and other related emissions and impacts of aviation on the climate [4], likewise Fleming and Ziegler [5] and Filippone [6] – to name just a few examples. Reducing the effects of global warming due to emissions has become a goal. As a result, reducing emissions has become an important issue. The commercial aviation industry has already developed and

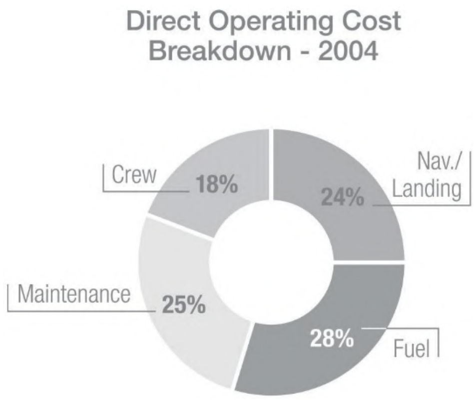

Figure 1. Operating Cost Breakdown.

implemented many techniques to reduce fuel consumption for reasons of economy and efficiency. On the operator side, these are mostly operational improvements, such as reducing the weight of on-board equipment or using a fixed ground power supply instead of the aircraft's auxiliary power unit on the ground. Airlines are searching fuel-efficient routes or flight profiles for most of the time. Measures to reduce noise and pollution are taken by airlines, airports and air navigation service providers in their daily operations [7].

Regulators to reflect the development of emission reduction and fuel saving. ICAO published Doc 10013 – Operational Opportunities to Reduce Fuel Burn and Emissions. It supposes the most effective way to minimize emissions: via the amount of fuel used [8]. For a given route fuel burn depends, if environmental aspects like weather or routing are said to be the same, on the weight of an aircraft. Specific range, flying at given altitude, temperature and speed, depends on aircraft mass. It is the physics of flight, that for an aircraft to fly it must generate lift to overcome its weight. The generation of the required lift and the movement of the airframe through the air create drag. The engines generate the necessary thrust to overcome this drag and enable the movement to generate lift (figure 2). The heavier the aircraft, the higher the fuel consumption. Fuel consumption, for carrying extra weight or extra fuel, is called Fuel Carriage Penalty (FCP). EASA gives a value of about 3 % difference in fuel consumption per kg and flight hour for additional weight [9]. ICAO Doc 10013 gives a value of 2.5 – 4.5 % additional fuel consumption, depending on the characteristics of the aircraft [8]. In addition, fuel savings can be made during climb since the lighter aircraft would reach it's optimal flight level earlier [10]. To minimize fuel burn it is most economical to carry the minimum required fuel for the sector.

New regulations will also be applied in the area of European regulations in 2022. EASA

Figure 2. Elementary forces on an airframe [10].

published Notice of Proposed Amendment (NPA) 2016-06, which follows a performance-based approach by updating the regulatory requirements for fuel planning, selection of aerodromes and in-flight fuel management, thus aims to increase operational efficiency and to have cost and environmental benefits [9]. This proposal to amend the regulations was followed by Opinion 2020-02 and finally by Regulation (EU) 2021/1296, which amends Operating Regulation (EU) 965/2012 in the area of Fuel/energy planning and management, support programmes and psychological assessment of flight crew, as well as testing of psychoactive substances. With the development of Commission Regulation (EU) 2021/1296, changes in ICAO Annex 6 have been transferred to the European regulatory. Fuel-related amendments to Annex 6 of the Convention on International Civil Aviation Organization (ICAO) and new guidance in ICAO document 9976 "Fuel planning manual" are to be incorporated into Regulation (EU) 965/2012 [11]. Various areas of the regulation shift, e. g. CAT.OP.MPA.150 is intentionally left blank and CAT.OP.MPA.151 is deleted [11]. CAT.OP.MPA.180 establishes new fuel/energy plan requirements for aircraft. For the fuel policy, until the adjustment in 2022, the following item was relevant: according to CAT.OP.MPA.150, the operator must establish a fuel policy and purpose of flight planning and in-flight replanning:

...to ensure that every flight carries sufficient fuel for the planned operation and reserves to cover deviations therefrom [12].

The fuel policy is transferred to the so-called Fuel Schemes. The consequences are illustrated below with the use of an example.

2. Methods

Fuel data of an operating airline were examined to explore a statistical background. The airline utilizes Boeing B777-200 aircraft in a freighter version. The operated network contains large airports, together with some local airports. The network destinations result in a mix of short, medium and long-haul flights. Planning and actual consumption were also evaluated. Here, two periods were considered in two steps: a five-year period covering all flights operated and a one-year period for extremely long long-haul flights with high loads.

In order to use the optimization possibilities in the area of fuel planning, which would be possible from 30^{th} October 2022, the corresponding prerequisites must be met. The GM2 to CAT.OP.MPA.180 of Regulation (EU) 965/2012 shows a non-exhaustive list of safety performance indicators (SPI) that can be used to measure safety performance [13]. This served as the reference point for the statistical fuel data evaluation.

In order to illustrate the possible optimisations, using the example of alternate fuel, the legal situation up to 30^{th} October and thereafter is compared below.

CAT.OP.MPA.150 Fuel policy, which will be omitted in the future, requires:

...(c) The operator shall ensure that the pre-flight calculation of usable fuel required for a flight includes: ...

(3) reserve fuel consisting of: ...

(ii) alternate fuel, if a destination alternate aerodrome is required ... [14]

Additional information on compliance with the implementing rules can be found in the Acceptable Means of Compliance (AMC). AMCs are non-binding standards adopted by EASA to illustrate means of determining compliance. Furthermore, there is Guidance Material (GM), as non-binding material for explanation and interpretation. So, in AMC1 CAT.OP.MPA.150 further explanations are given, regarding the content of the fuel policy:

... (4) Alternate fuel, which should:

(i) include:

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(A) fuel for a missed approach from the applicable DA/H or MDA/H at the destination aerodrome to missed approach altitude, taking into account the complete missed approach procedure;
(B) fuel for climb from missed approach altitude to cruising level/altitude, taking into account the expected departure routing;
(C) fuel for cruise from top of climb to top of descent, taking into account the expected routing;
(D) fuel for descent from top of descent to the point where the approach is initiated, taking into account the expected arrival procedure; and
(E) fuel for executing an approach and landing at the destination alternate aerodrome;... [14]

Figure 3, figure 4 and figure 5 illustrate the possible consequences of the regulatory changes and optimisation options.

Figure 3 shows the missed approach procedure for Runway 26L of the instrument approach for Leipzig Airport (EDDP). In the event of a missed approach, the blue dashed path should be flown, highlighted in green. The corresponding description of the instrument flight procedure

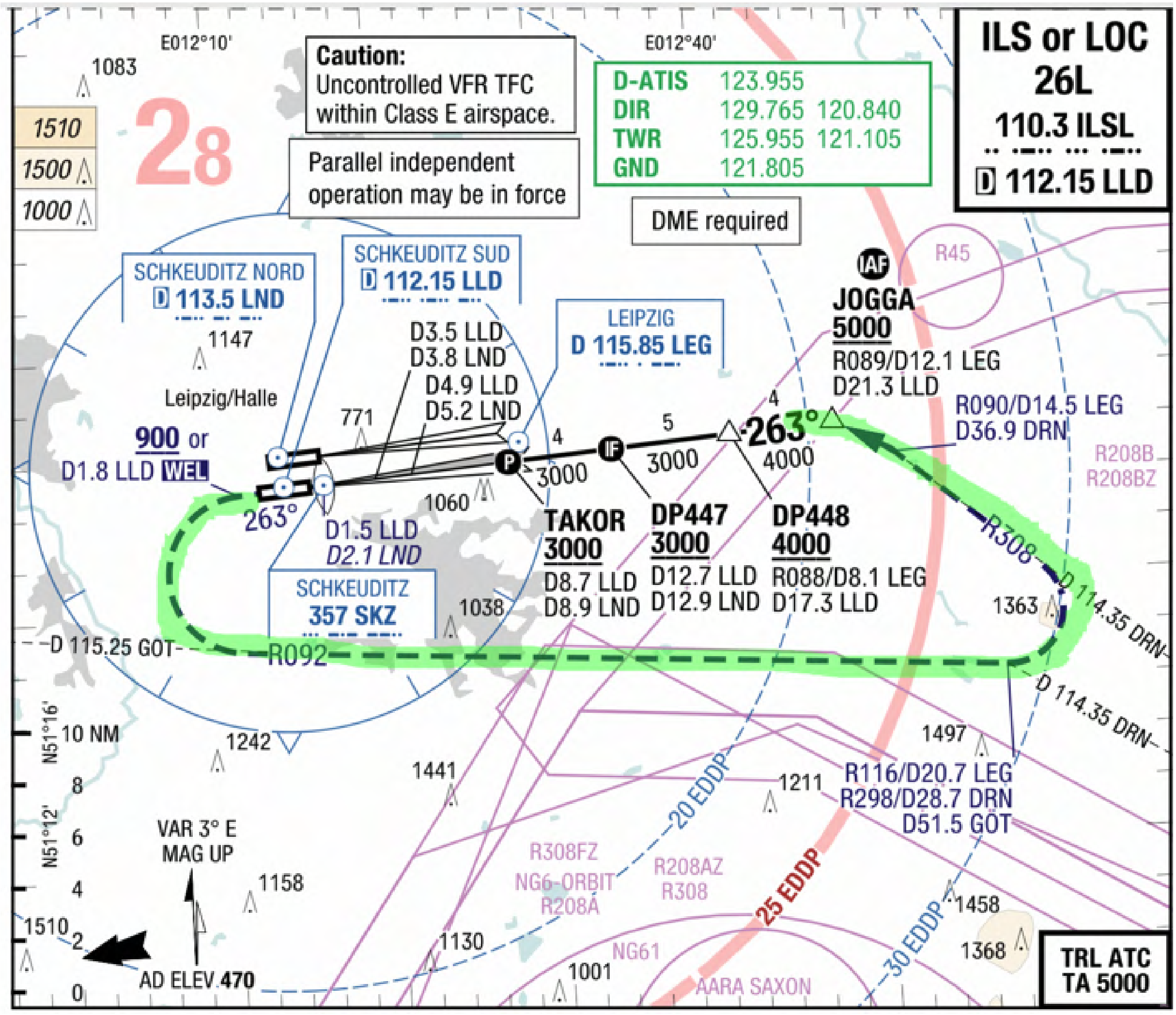

Figure 3. Leipzig Airport Misses Approach Procedure Track [15].

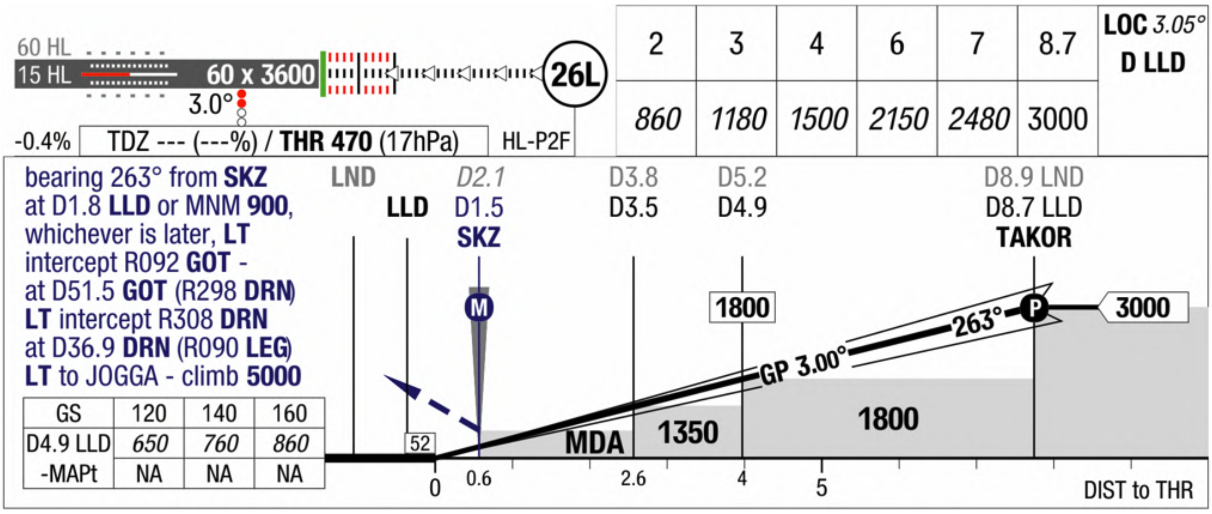

Figure 4. Leipzig Airport Missed Approach Procedure description [15].

can be found in figure 4. As can be seen above, according to the current requirements, the complete missed approach must be taken into account in the planning – here this is approx. 45 – 50 nautical miles, or approx. 12 minutes flying time, to the start of the new approach.

In practice, however, it must be taken into account that, in the event of a missed approach, radar guidance is usually quick and the entire track is not usually flown. In only a few cases does a missed approach occur at all. In the case of a missed approach to the destination alternate airport, this airport may be located in a completely different direction, so that the aircraft would fly directly in this direction after a missed approach.

Figure 5 shows an example of such planning. Here, the approach to Leipzig is planned in a westerly direction. The alternate airport is also in a westerly direction, it is Erfurt (EDDE). Unless a new approach is attempted in Leipzig, the direct route to Erfurt will certainly be chosen

Figure 5. Erfurt as Alternate Airport [16].

without flying the entire missed approach. For these three reasons (infrequent need for a missed approach, often shorter route in the case of a second approach, and a more direct route in the case of a diversion under certain circumstances), a reduction of the fuel required in the planning can be considered. The regulatory basis is presented next.

As mentioned above, the fuel policy will be converted into a fuel scheme. The requirements for this can be found in CAT.OP.MPA.180 Fuel/energy scheme – aeroplanes.

(a) The operator shall establish, implement, and maintain a fuel/energy scheme that:

(1) is appropriate for the type(s) of operation performed;

(2) corresponds to the capability of the operator to support its implementation; and

(3) is either:

(i) a basic fuel/energy scheme, which shall form the basis for a basic fuel/energy scheme with variations and an individual fuel/energy scheme; the basic fuel/energy scheme derives from a large-scale analysis of safety and operational data from previous performance and experience of the industry, applying scientific principles; the basic fuel/energy scheme shall ensure, in this order, a safe, effective, and efficient operation of the aircraft; or

(ii) a basic fuel/energy scheme with variations, which is a basic fuel/energy scheme where the analysis referred to in point (i) is used to establish a variation to the basic fuel/energy scheme that ensures, in this order, a safe, effective, and efficient operation of the aircraft; or

(iii) an individual fuel/energy scheme, which derives from a comparative analysis of the operator's safety and operational data, applying scientific principles; the analysis is used to establish a fuel/energy scheme with a higher or equivalent level of safety to that of the basic fuel/energy scheme that ensures, in this order, a safe, effective, and efficient operation of the aircraft.

In the associated GM1 to CAT.OP.MPA.180 explanations are given on the AMC to be applied. In principle, an operator may choose between three different fuel schemes. The following AMCs apply to the development of each fuel scheme:

(a) Basic fuel scheme: all the AMC that apply to the basic fuel scheme.

(b) Basic fuel scheme with variations: when an operator decides to deviate fully or partly from the basic fuel schemes, the AMC for basic fuel schemes with variations apply to the specific deviation.

(c) Individual fuel scheme: when an operator wishes to apply an individual fuel scheme, the AMC for the individual fuel scheme apply; for the part of the scheme where the operator still follows the basic fuel scheme, the operator should apply the AMC referred to in (a) and (b) [14].

Depending on the chosen level of the scheme, different AMCs, if any, are applied. As previously in CAT.OP.MPA.150, in future in CAT.OP.MPA.181 Fuel/energy scheme – fuel/energy planning and inflight re-planning policy – aeroplanes the requirements for the destination alternate fuel are listed:

(4) destination alternate fuel/energy:

(i) when a flight is operated with at least one destination alternate aerodrome, it shall be the amount of fuel/energy required to fly from the destination aerodrome to the destination alternate aerodrome; or... [14]

However, the supplementary AMC1 to CAT.OP.MPA.181 only refers to the basic fuel scheme for Performance Class A aeroplanes. Performance Class A refers to multi-engine aircraft powered by turbojet or turboprop engines that can carry more than nine passengers or weigh more than

5 700 kilograms. In terms of content, the requirements in point (d) corresponds in principle to AMC1 of CAT.OP.MP.150 (see above). However, if companies choose a basic fuel scheme with variations or an individual fuel scheme, the AMC is not applicable. As a consequence, consideration could be given, for example, to reduce the amount of alternative fuel, e. g. based on statistical experience. This can result in savings, which are presented below.

The examples shown below are based on statistical fuel data from a globally operating cargo airline. Boeing 777 freighter aircraft are used. For the statistical evaluation, various information was provided via the reporting system. Numerous information can be condensed from the reports. Over a period of five years, for which the data were available, the following points were especially found:

- 187 flights, equals 0.59% of 31 315 flights, where planned with no alternate (fuel),
- six flights, out of 39 467 flights, could be identified as have to be diverted, which gives a diversion rate of 0.015%.

This information shows the rare event of landing at the alternate airport and the equally rare legal possibility of planning without an alternate airport (where additional fuel must be planned for 15 minutes of flight time). As shown above, when using a basic fuel scheme with variations or an individual fuel scheme, the AMC1 to CAT.OP.MPA.181 is not necessarily applicable. Airlines could, based on statistical data and a corresponding risk assessment, make a reduction in the planned alternate fuel compared to the current planning/requirement.

In the following it is assumed that a reduction of the alternative fuel by 5 minutes is possible. This corresponds to a value of approx. 700 kg of fuel for a Boeing 777-200 freighter examined. This value can be derived from the final reserve fuel plan – which provides for 30 minutes of flight time at 1500 feet above the airfield. In figure 6 and figure 7 an excerpt from the operational flight plan is presented, in particular the fuel planning and the mass and loading. Figure 6 shows the comparison of fuel planning for a flight from Hong Kong to Leipzig. Since the current approved planning program does not allow a reduction of the alternate fuel, the value of 5 minutes of fuel was included as additional fuel, for comparison. On the left is the original plan, on the right the plan with 5 minutes more fuel.

The values for alternate and final reserve fuel shown in figure 6 do not correspond to those that would result from an actual reduction of the alternate fuel by 5 minutes. The 700 kg / 5 minutes in the right column only affects trip and contingency fuel, but not per legal requirements needed alternate and final reserve fuel. With a real alternate fuel reduction, these values would also be lower and would lead to a more significant reduction in trip and contingency fuel. Therefore, the resulting delta, in this case an additional consumption of 257 kg, is lower than the actual savings would be. This would be possible in the case of alternate fuel reduction. But the trend and thus a rough figure for evaluation is evident. The average additional consumption for this route is 21.34 kg/flight hour, i.e. this would be the savings potential. In the lower part, the corresponding weight information is also listed as a comparison. As can be seen, 700 kg of extra fuel led to a reduction of the maximum possible load from 1 548 kg before to 589 kg after. Here too, a reduction of the alternate fuel would be correspondingly positive. Figure 7 shows the same considerations for the route Hong-Kong to Cincinnati. Here, the difference in fuel, i.e. the savings potential, is 364 kilograms. The average additional consumption for this route is 25.1 kg/flight hour, i.e. this would be the savings potential in this case.

Both examples show the savings opportunities. A single aircraft, with an average flight time of 15 hours, would consume something like 300 kg less fuel per day. Even if these savings seem small, already with a relatively small fleet of only 20 aircraft, the total value is correspondingly high. A conservative projection of 20 kg/flight hour and 15 hours flight time per day with twenty aircraft results in potentially 6 000 kg fuel saving per day. The associated savings in emissions of carbon dioxide are ∼18 900 kg, water ∼7 500 kg and 30 to 150 kg nitrogen oxides per day

		SKD	FLTT	TTL DIST	5519	
	VHHH/HKG	0940	1003			
	EDDP/LEJ	2240	2211			
	HRS	1240	1208			
	Origin			700 kg extra		Δ
TRIP	102090	12:08		102342	12:08	252
CONT 3%	3063	00:22	EPKT	3070	00:26	7
ALTN	3832	00:27	EDDV	3832	00:27	
FINRES	3136	00:30		3136	00:30	
REQTOF	112121	13:03		112380	13:03	
REQTOF	112200			112400		
ADDFU				700	00:05	
TAXI	767	00:23		767	00:23	
Origin		Load		ZFW	TOW	LW
DOW	UNDR	1548	MAL	248115	347450	260815
141781	PTTL	92000	PLN	233781	345902	243812
700 kg extra	UNDR	589	PLN	233781	346861	244519
Δ		959			959	707

Figure 6. Comparison route Hong Kong – Leipzig.

		SKD	FLTT	TTL DIST	7871	
	VHHH/HKG	1350	1413			
	KCVG/CVG	0515	0444			
	HRS	1525	1431			
	Origin			700 kg extra		Δ
TRIP	117295	14:31		117649	14:31	354
CONT 3%	3519	00:26	KDSM	3529	00:26	10
ALTN	3326	00:27	KSDF	3326	00:27	
FINRES	2968	00:30		2968	00:30	
REQTOF	127108	15:54		127472	15:54	
REQTOF	127200			127500	.	
ADDFU				700	00:05	
TAXI	767	00:23		767	00:23	
origin		Load		ZFW	TOW	LW
DOW	UNDR	2061	MAL	248115	347450	260815
141781	PTTL	76500	PLN	218281	345389	228094
700 kg extra	UNDR	997	PLN		346453	228804
Δ		1064			1064	710

Figure 7. Route Comparison Hong Kong – Cincinnati.

– for a fleet of 20 aircraft. These figures are based on the indication that carbon dioxide and water vapor are the most abundant products of jet fuel combustion, with emission indices for CO2 and H2O of 3.15 kg/kg fuel and 1.26 kg/kg fuel burned [17]. These considerations are conservative and do not consider all the other advantages of a lighter aircraft. The values of

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21 – 25 kg of additional fuel consumption determined above correspond to a fuel penalty factor of approx. 3%. In the further consideration of the savings effects, the savings of the 5-minute fuel weight (here 700 kg for 5 minutes) and the additional consumption added up per flight hour must also be considered as freight delta cumulatively. For the two flights examined above, this results in approx. 1 000 kg difference for freight at take-off.

3. Results

As part of an overarching study, statistical flight data of an airline were analysed over a period of five years. In the first step, information on individual fuel components was examined. In the second step, long flights with high freight volumes were examined in more detail with regard to planning and actual consumption. Analysis of the fuel data has shown that consumption in planning and in practice is at a high and reliable level. As a result of this evaluation, an approach to reducing the alternative fuel consumption is possible. This is based on changes in the underlying operational regulations.

A reduction of fuel has an impact on overall fuel and emission reduction. On this basis, it is recommended that airline operators may evaluate their operational procedures, management- and safety system in preparation of the implementation of a choose a basic fuel scheme with variations or an individual fuel scheme. This allows the planning of lower fuel quantities, reducing emissions.

Evaluation in Piano-x and further reduction of other fuel values possible.

Figure 8 shows almost no difference for an single flight, in the end the results are quit clearly, seen over a year.

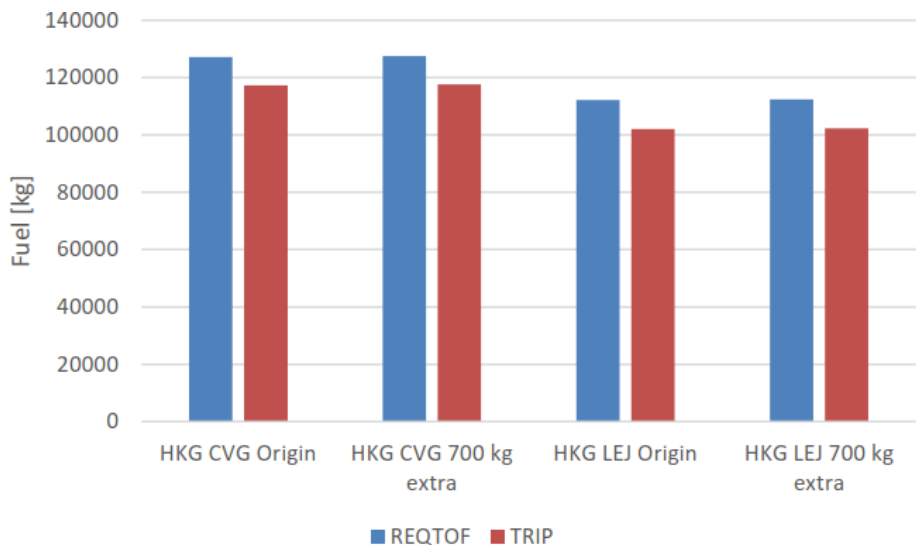

Figure 8. Impact of 5 minutes of fuel.

4. Discussion

The above proposal is the starting point for consideration. Improved risk assessment, calculations based on better data and better decision-making can optimise the amount of additional fuel needed without compromising safety levels. Aviation remains committed to progress towards climate-neutral aviation by 2050 [18]. New concepts are also necessary for this. Further research is needed to identify safety and performance indicators. An in deep evaluation of planning and used alternate fuel figures is recommended. Reducing the fuel components can free up space for additional cargo, which in turn can reduce the total number of flights required. Further considerations should be made here.

Further research is needed to identify performance indicators. The above assessment has focused only on one fuel component. A more in-depth assessment of total fuel numbers is recommended, as well as consideration of other factors such as aircraft system reliability, the influence of weather or airfield processes. Based on these investigations, a risk assessment can be made to further reduce the amount of fuel carried.

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References

[1] ICAO 2019 Annual Report 2019: Presentation of 2019 Air Transport statistical results URL https://www.icao.int/annual-report-2019/Documents/ARC_2019_Air%20Transport%20Statistics.pdf
[2] IATA 2019 *Economic Performance of the Airline Industry* URL https://www.iata.org/en/iata-repository/publications/economic-reports/airline\-industry-economic-performance---december-2019---report
[3] Airbus 2008 *Getting to grips with A320 Family Performance Retention and Fuel Saving* (*Flight Operations Support & Services* no 2) (Blagnac Cedex: AIRBUS S.A.S.) URL https://www.cockpitseeker.com/wp-content/uploads/goodies/ac/a320/pdf/data/GTGA320PerfoRetentionIssue2.pdf
[4] Lee D S, Fahey D W, Forster P M, Newton P J, Wit R C, Lim L L, Owen B and Sausen R 2009 *Atmospheric Environment* **43**(22-23) 3520–3537 ISSN 1352-2310 URL https://doi.org/10.1016/j.atmosenv.2009.04.024
[5] Fleming G G and Ziegler U 2016 *ICAO Environmental Report* URL https://www.icao.int/environmental-protection/Documents/EnvironmentalReports/2016/ENVReport2016_pg16-22.pdf
[6] Filippone A 2008 *Journal of Aircraft* **45**(1) 185–197 ISSN 0021-8669 URL https://doi.org/10.2514/1.31422
[7] IATA 2019 *Aircraft Technology Roadmap to 2050* URL https://www.iata.org/contentassets/8d19e716636a47c184e7221c77563c93/technology20roadmap20to20205020no20foreword.pdf
[8] ICAO 2014 *Doc 10013 – Operational Opportunities to Reduce Fuel Burn and Emissions* 1st ed (*Doc* vol 10011-AN/506) (Montréal: International Civil Aviation Organization) ISBN 978-92-9249-563-3
[9] European Aviation Safety Agency 2016 Notice of Proposed Amendment 2016-06 (A): Fuel planning and management URL https://www.easa.europa.eu/downloads/21129/en
[10] Airbus 2004 *Getting to grips with fuel economy* (*Flight Operations Support & Services* no 4) (Blagnac Cedex: AIRBUS S.A.S.) URL https://ansperformance.eu/library/airbus-fuel-economy.pdf
[11] European Commission 2021 Commission Implementing Regulation (EU) 2021/1296 URL https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32021R1296&from=DE
[12] European Union Aviation Safety Agency 2020 Easy Access Rules for Air Operations — Revision 19 URL https://www.iata.org/en/publications/economics/fuel-monitor/
[13] European Union Aviation Safety Agency 2020 Appendix to Opinion No 02/2020 URL https://www.easa.europa.eu/downloads/119252/en
[14] European Union Aviation Safety Agency 2022 Easy Access Rules for Air Operations URL https://www.easa.europa.eu/sites/default/files/dfu/easa_asr_2020.pdf
[15] LufthansaSystems 2022 Lido Charts URL https://www.lhsystems.de/solutions-services/flight-deck-solutions/lidonavigation/lidoroutemanual
[16] Aircraft IT 2022 EFB Weather Awareness Solution (eWAS) App Demo and Overview Webinar URL https://www.aircraftit.com/webinars/sitaonair-efb-weather-awareness-software-solution-ewas-app-demo-on-demand-webinar/#&gid=1&pid=4
[17] Penner J E, Lister D H, Griggs D J, Dokken D J and McFarland M (eds) 1999 *Aviation and the Global Atmosphere* (Cambridge: Cambridge University Press) URL https://archive.ipcc.ch/ipccreports/sres/aviation/index.php?idp=0
[18] European Aviation Safety Agency 2020 *Annual Safety Review 2020* (Cologne: European Union Aviation Safety Agency) ISBN 978-92-9210-222-7 URL https://www.easa.europa.eu/sites/default/files/dfu/easa_asr_2020.pdf

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Research into the transverse loading of the container with sandwich-panel walls when transported by rail

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Research into the transverse loading of the container with sandwich-panel walls when transported by rail

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Abstract. The article presents the results of the research into the transverse loading of the container during rail transportation. The peculiarity of the container is its walls made of sandwich panels. Such a solution will help to reduce the dynamic loading on the container in operation and, accordingly, improve its strength. Appropriate calculations have been carried out in order to determine the optimum (minimum) sheet thickness, provided that the permissible deflection in operation is ensured. The transverse loading on the container placed on a flat wagon at the side rolling has been investigated. It is found that the acceleration value obtained is almost 5% lower than that acting on the container of a typical design. The strength of the container with sandwich-panel walls is calculated using the finite element method. The results of the calculation show that the maximum stresses are 6% lower than those occurring in the container of a typical design. The research may be of values for those who develop recommendations for designing advanced modular vehicles and improving the efficiency of transportation.

1. Introduction

The efficient performance of the machine-building industry requires development and putting into operation modern structures of vehicles. For a long time railway transport has been the most competitive industry of machine engineering, which accounts for a large proportion of freight transportation [1].

The experience of development of the wagon fleet in the UIC member countries indicates a steady trend in improving the level of traffic safety, which ensures operational reliability and environmental compatibility of vehicles. At the same time, one of the most optimal solutions to achieve these requirements is the introduction of modular vehicles, in particular, containers, into operation.

In addition to a number of advantages of these vehicles in operation compared to others, there are also significant disadvantages associated with insufficient strength of their structures. The reason for it is significant operational loads, including dynamic sign-variable ones affecting the vehicles. These loads affect not only the container, but also the freight inside. Due to the fact that this freight has its own degree of freedom, the container structure can have additional loading. And this loading can damage the container (figure 1 [2]).

This requires additional maintenance costs. Besides, it can also affect the traffic safety and cause ecological damage.

(a) (b)

Figure 1. Damage to containers in operation: (a) design diagram of a flat wagon; (b) deformation and cracks in the cover.

Therefore it is important to research into structural improvements for containers in order to reduce their dynamic loading at operational modes.

Research devoted to the structural improvements in the container is quite relevant, which is confirmed by a large number of publications. For example, in article [3] the authors propose and substantiate the design of a container for fruit and vegetable products. All structural solutions regarding the improvements in the container are confirmed by appropriate strength calculations. The study presents main operational loading diagrams for containers.

Also, the design of a container for transportation of fruit and vegetable products is proposed in [4]. The study presents the results of strength calculation and the operational requirements for the container. At the same time, when designing these container structures, the authors did not propose any solution to improve the strength of container walls.

Special features of designing the ISO container are studied in [5]. The main loading diagrams for the container in operation are analysed, as well as the structural resistance to external loads. However, it should be noted that the improvements proposed in this work do not increase the strength of container walls when containers are transported either by rail or by other transport mode.

To reduce the dynamic loads on vehicles and, thereby, improve their strength characteristics, it is advisable to use sandwich panels in their structures. The use of sandwich panels in the rail vehicle design is substantiated in [6]. The study presents an algorithm for optimizing the bearing structure of a vehicle. The results of the calculations demonstrate that this solution contributes to a 16.36% reduction in the bearing structure if compared to the prototype.

The use of sandwich panels in the vehicle body structure is also substantiated in studies [7,8]. The research was carried out on the example of a rail car. These solutions are implementable in both manufacture and modernization of rail cars. The feasibility of the proposed solutions has been proved by theoretical calculations of the strength for the bearing rail car structure.

A similar solution is proposed in [9]. The author's team focus on improving the reliability of the bearing structure of a vehicle by introducing composite panels. It was proven that the use of such panels could improve the endurance of vehicle bodies.

However, it should be noted that the authors of these studies did not consider the use of sandwich panels for the structure of removable vehicles, in particular, containers.

The review of literature allows us to conclude that the issues of improvements for the container are quite relevant. At the same time, their higher strength by means of sandwich panels in the bearing structures has not yet been thoroughly studies. In this regard, there is a need to conduct research in this area.

The objective of the study is to highlight the results of determining the transverse dynamics and the strength of a container with sandwich panel walls when transported by rail. To achieve the objective the following tasks were set:

- to substantiate the structural solutions to make the container sidewalls of sandwich panels;
- to determine the transverse dynamics of the container;
- to calculate the container strength.

2. The substantiation of the structural solution to make the container sidewalls of sandwich panels

It is proposed to introduce sandwich panels as the components of container sidewalls to ensure their strength. The sandwich panels are composed of two metal sheets with an energy-absorbing material between them (figure 2). Such a solution will improve the strength of the container by reducing its loading.

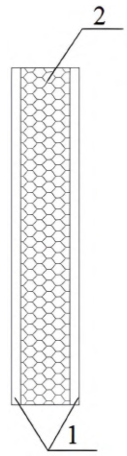

Figure 2. Sandwich-panel construction: 1 – metal sheet, 2 – energy-absorbing material.

Appropriate calculations were carried out to determine the thickness of the cover sheet of the container. The cover sheets for each section were considered as thin-walled slabs with a width of 6.058 m and a height of 2.591 m.

The sheet thickness was determined by the formula [10]:

$$\delta = \sqrt{\frac{P \cdot 96 \cdot (b^2 + \mu \cdot a^2) \cdot a^2 \cdot b^2}{\sigma \cdot \pi^4 \cdot (a^2 + b^2)^2}}, \tag{1}$$

where P – the pressure acting on the sheet area; σ – the allowable stresses of the material of the cover; a – the sheet width; b – the sheet height; μ – Poisson's ratio; π – to constant, which is equaled to 3.14.

On the basis of the calculations it was found that at $[\sigma] = 210$ MPa, $\mu = 0.28$ (steel), the transverse force value $0.6 \cdot P_k \cdot g$, where P_k – the carrying capacity of the container, the value $\delta = 1.6$ mm. Taking this into account, the thickness of the energy-absorbing layer can be taken as 32.8 mm, based on the condition of maintaining the wall size within that of a typical container.

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3. The determination of the transverse dynamics of the container with sandwich panel walls

To substantiate the use of sandwich panels in the sidewalls of the container, mathematical modelling of its dynamic loading was carried out, provided that the container was placed on a flat wagon at side rolling oscillations. The design diagram of the container placed on the flat wagon is shown in figure 3.

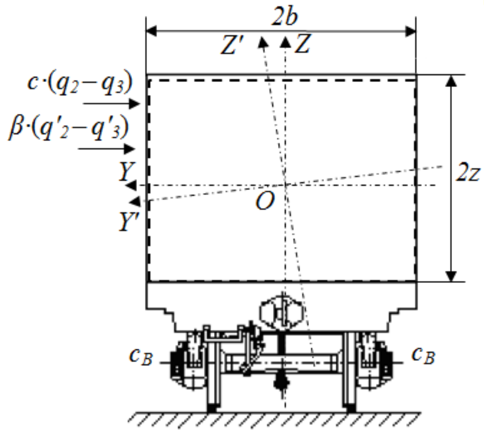

Figure 3. The design diagram of the container placed on the flat wagon.

For this purpose, mathematical model (2) was formed.

$$\begin{cases} I_{FM} \cdot \ddot{q}_1 + c_B \cdot b \cdot (sign(b \cdot q_1)) = F_C; \\ I_C \cdot \ddot{q}_2 - g \cdot (M_k \cdot z^2) \cdot q_2 = F_{FM} + F_f - c \cdot b^2 \cdot (q_2 - q_3) - \beta \cdot b^2 \cdot (\dot{q}_2 - \dot{q}_3); \\ I_f \cdot \ddot{q}_3 = F_C - c \cdot b^2 \cdot (q_2 - q_3) - \beta \cdot b^2 \cdot (\dot{q}_2 - \dot{q}_3), \end{cases} \quad (2)$$

where I_{FM} – the inertia moment of the flat wagon; c_B – the stiffness of the springs of the suspension group of the bogie; b – the half-width of the flat-wagon frame; F_C – the moment of forces occurring between the container and the flat wagon frame; I_C – the inertia moment of the container relative to the longitudinal axis; g – the free fall acceleration; M_k – the mass of the container; z – the half-height of the container; F_{FW} – the moment of forces occurring between the flat wagon and the container; F_f – the moment of forces occurring between the container and the freight; c – the stiffness of the energy-absorbing material; β – the viscous resistance coefficient of the energy-absorbing material; I_f – the inertia moment of the freight; q_1, q_2, q_3 – the generalised coordinates that determine the movement of the flat wagon, container and freight, respectively.

Mathematical model (2) was solved in MathCad at the initial conditions equalling zero [11–13]. The model was reduced to the normal Cauchy form with a subsequent solution according to the Runge-Kutta method [14–16]. On the basis of the calculation it was found that the maximum accelerations to the container were 1.7 m/s^2 (figure 4).

The value of the acceleration obtained was almost 5% lower than that to the container of a typical design. The calculation was made at the stiffness coefficient of the energy-absorbing material 1.5 kN/m and the viscous resistance coefficient 2.0 kN·s/m. These parameters were determined by a sequential selection, provided that the accelerations were within the permissible values.

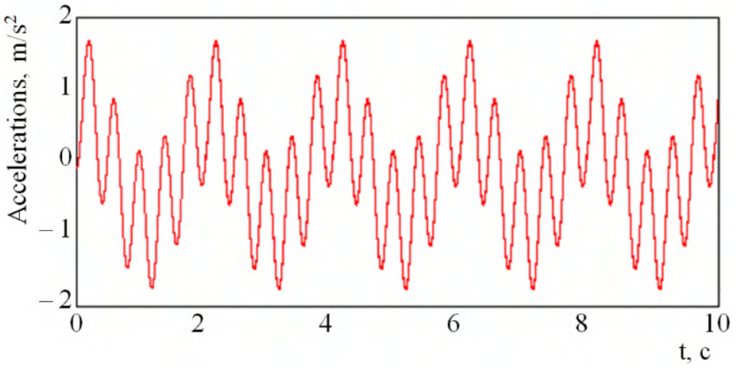

Figure 4. Accelerations to the container.

4. The strength calculation for the container with sandwich-panel walls

The resulting acceleration value was included in the strength calculation of the container. The spatial model of the container was built in SolidWorks (figure 5). It included the structural elements rigidly interacting with each other. The strength calculation was made in SolidWorks Simulation with the finite element method. The Mises criterion was used as the calculation criterion [17, 18].

The viscoelastic connection in the sandwich panels that form the sidewalls was included as the spring-damper connection by means of the software complex options (figure 6).

The design diagram of the container included the following loads (figure 7): vertical static P_v, transverse P_t applied to the sidewall. The transverse loading included the pressure from the freight (grain), as well as the dynamic loading. The dynamic loading was applied from the container slope side.

The pressure from the freight to the container walls was determined with the Coulomb method using Sinelnikov's adjustment:

$$p = \gamma \cdot h \cdot \frac{\cos^2 \cdot (\rho - \alpha)}{[1 + \sqrt{\frac{\sin\rho \cdot \sin(\rho - \alpha)}{\cos\alpha}}]^2 \cdot \cos\alpha}, \tag{3}$$

where γ – the volumetric mass of the freight; h – the container height; ρ – the angle of the internal friction; α – the angle of inclination of the container (taken equal to about 6°).

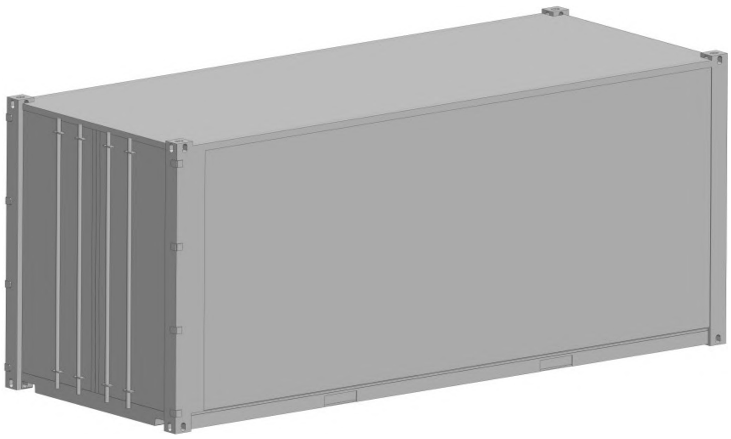

Figure 5. 1CC container with sandwich-panel walls.

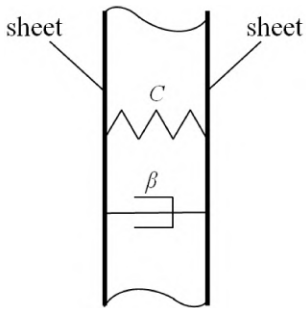

Figure 6. Diagram of viscoelastic bonds in the container walls.

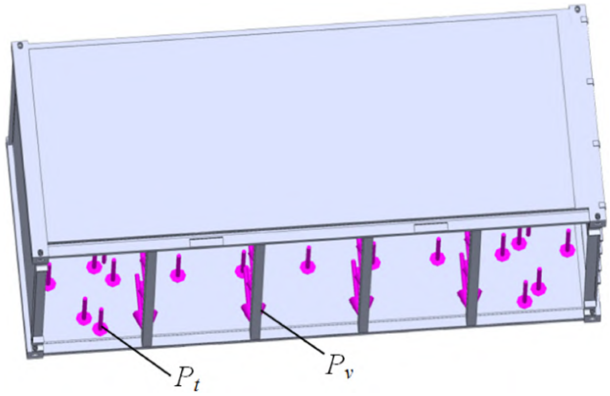

Figure 7. Calculation diagram of the container.

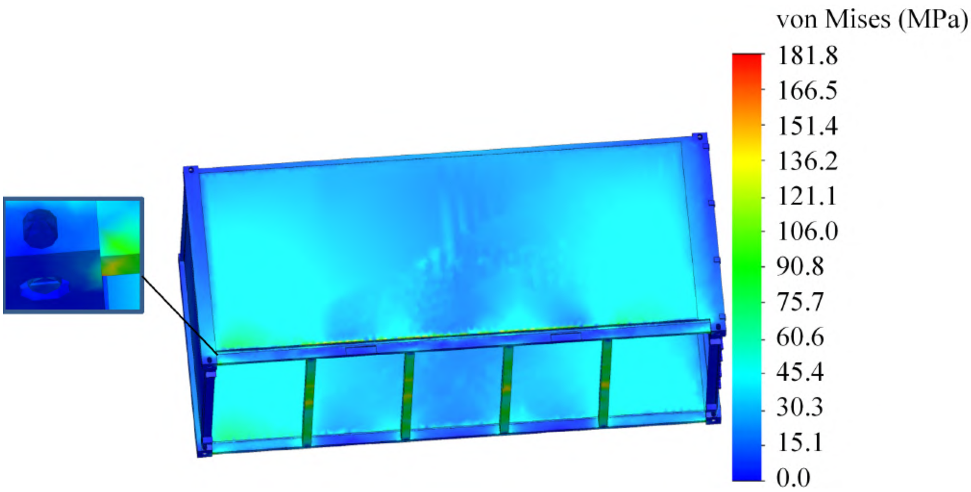

Figure 8. Stress state of the container.

When building the finite-element model of the container, spatial tetrahedrons were used. The model consisted of 373575 nodes and 11119509 elements. The maximum element size was 80 mm and the minimal element size was 16 mm.

The model was secured by fittings. Steel 09C2Cu was used as the structural material [19,20]. The results of the calculation are given in figure 8.

The maximum stresses were recorded in the contact areas between the bottom side rail and the fitting stops; they amounted to about 180 MPa (stress in the external layer). The resulting stresses were 6% lower than those in a typical container design.

The research conducted will be of value for those who develop recommendations for designing advanced structures of modular vehicles and improving the efficiency of transportation.

5. Conclusions

The structural solution to make the container sidewalls of sandwich panels has been substantiated. In this case, the thickness of the sheets that form the sandwich panel should be 1.6 mm, thus ensuring their strength. The thickness of the energy-absorbing layer can be taken as 32.8 mm, while observing the wall size within that of a typical container.

The research deals with determination of the transverse dynamics of the container with sandwich-panel walls. The maximum accelerations on the container are 1.7 m/s^2. The value of the acceleration obtained is almost 5% lower than that acting to the container of a typical design. The calculation is made at the stiffness coefficient of the energy-absorbing material 1.5 kN/m and the viscous resistance coefficient 2.0 kN·s/m).

The research also includes the strength calculation for the container with sandwich-panel walls. The results of the calculation show that the maximum stresses occur in the contact areas between the bottom side rail and the fitting stops; they are equal to about 180 MPa. It should be noted that the resulting stresses are 6% lower than those occurring in a typical container design.

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References

[1] Lewandowski K 2006 *Sistemy transportowe* (6) 53–55 URL https://yadda.icm.edu.pl/baztech/element/bwmeta1.element.baztech-article-BGPK-1398-5437/c/Lewandowski.pdf
[2] 2014 URL https://ppt-online.org/20611
[3] Ybrahymov N N, Rakhymov R V and Khadzhymukhamedova M A 2015 *Molodoi uchenii* **21(101)** 168–173 URL https://moluch.ru/archive/101/22929/
[4] Khadzhymukhamedova M A and Merganov A M 2020 *International Journal of Recent Technology and Engineering (IJRTE)* **8**(5) 2277–3878 URL http://www.doi.org/10.35940/ijrte.E4856.018520
[5] Sugianto 2020 *INTEK: Jurnal Penelitian* **7**(2) 92–100 URL https://doi.org/10.31963/intek.v7i2.2625
[6] Al-Sukhon A and ElSayed M S 2022 *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit* **236**(8) 920–935 URL https://doi.org/10.1177/09544097211049640
[7] Płaczek M, Wróbel A and Olesiejuk M 2017 *MATEC Web of Conferences* **112** 06022 URL https://doi.org/10.1051/matecconf/201711206022
[8] Chuan-jin O and Bing-tao L 2020 *E3S Web of Conferences* **145** 02001 URL https://doi.org/10.1051/e3sconf/202014502001
[9] Wróbel A, Płaczek M and Buchacz A 2017 An Endurance Test of Composite Panels *Mechatronic Systems and Materials VIII* (*Solid State Phenomena* vol 260) (Trans Tech Publications Ltd) pp 241–248 URL https://doi.org/10.4028/www.scientific.net/SSP.260.241
[10] Bezukhov N 1957 *Hosudartvennoe yzdatelstvo tekhnyko-teoretycheskoi lyteraturi*
[11] Lovskaya A 2014 *Eastern-European Journal of Enterprise Technologies* **3** 36–41 URL https://doi.org/10.15587/1729-4061.2014.24997
[12] Nalapko O, Shyshatskyi A, Ostapchuk V, Mahdi Q A, Zhyvotovskyi R, Petruk S, Lebed Y, Diachenko S, Velychko V and Poliak I 2021 *Eastern-European Journal of Enterprise Technologies* **1**(9 (109)) 18–32 URL https://doi.org/10.15587/1729-4061.2021.225331
[13] Dudnyk V, Sinenko Y, Matsyk M, Demchenko Y, Zhyvotovskyi R, Repilo I, Zabolotnyi O, Simonenko A, Pozdniakov P and Shyshatskyi A 2020 *Eastern-European Journal of Enterprise Technologies* **3**(2 (105)) 37–47 URL https://doi.org/10.15587/1729-4061.2020.203301
[14] Domin Y V and Chernyak G Y 2003 *Osnovi dinamiki vagoniv* (Kyiv: KUETT)
[15] Zadachyn V M and Koniushenko I H 2014 *Chyselni metody*

[16] Hoi T P and Makhnei O V 2012 *Dyferentsialni rivniannia*
[17] Panchenko S, Vatulia G, Lovska A, Ravlyuk V, Elyazov I and Huseynov I 2022 *EUREKA: Physics and Engineering* (6) 45–55 URL https://doi.org/10.21303/2461-4262.2022.002638
[18] Rzeczycki A and Wiśnicki B 2016 *Solid State Phenomena* **252** 81–90 URL https://doi.org/10.4028/www.scientific.net/SSP.252.81
[19] 2014 DSTU 7598:2014 Vagoni vantazhni. Zagalni vimogi do rozrahunkiv ta proektuvannya novih i modernizovanih vagoniv koliyi 1520 mm (nesamohidnih)
[20] 2010 BS EN 12663-2:2010 Railway applications. Structural requirements of railway vehicle bodies Freight wagons

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Determination of the thermal stress state for the composite brake pad of a wagon at operational loads

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Abstract. The article provides the results of determining the thermal stress state of the composite brake pad of a wagon. The research is made by means of computer simulation with the finite element method using the SolidWorks Simulation options. The design diagram of the pad includes not only the horizontal loads due to its pressing to the rolling surface of the wheel and the friction force, but also the temperature impact taken equal to 400°C. Since the composite material of the pad is fragile, the Mohr–Coulomb criterion is used as a calculation criterion. It has been found that the maximum stresses occur in the upper part of the pad in the contact area between the back plate and the side plate and do not exceed the permissible values. The article presents the results of the calculation of the thermal stress state of the pad with dual wedge-shaped wear. The study includes the actual parameters of the pad wear determined during operational research. The results of the calculation show that the maximum stresses occur in the back plate of the pad and exceed the permissible values by 19.8%. This is explained by the fact that the useful area of the pad decreases, and therefore its loading increases. The research conducted proves the negative impact of dual wedge-shaped wear on the braking efficiency and the strength of the brake pad. This requires development of measures for eliminating this wear.

1. Introduction

The rapid development of the rail industry is accompanied by an increase of the train speed and the axle loading, the need to improve the structures and materials for the rolling stock, an increase in the tare load ratio of rail cars, etc. [1]. In this regard, friction materials used in the railway industry, in particular, for braking systems, should provide a fixed friction coefficient and low wear at various operational (speed, temperature, pressure) and environmental (noise, extreme weather) conditions.

The violation of the operational requirements causes an increased wear of brake pads (figure 1), and therefore, in operation brake shoes can be used for braking. This certainly leads to damage to the rolling surfaces of the wheels and directly affects the train traffic safety.

Therefore, in order to prevent abnormal wears of brake pads, including dual wedge-shaped wear, it is advisable to develop requirements and devices that will ensure the uniform wear of brake pads so that they can serve during the whole repair-to-repair period at depots. This makes it possible to dispose of such brake pads with a minor portion of the working composite mass remaining and save hundreds of thousands of hryvnias for Ukrainian Railways or industrial enterprises with their own freight rolling stock, so that they will purchase brake pads and significantly reduce operational costs.

(a) (b)

Figure 1. Consequences of abnormal wear of composite brake pads: (a) damaged brake shoe with wire instead of the key, used for braking without a pad; (b) part of the damaged pad remaining in the brake shoe.

The issue of traffic safety of freight trains is quite relevant and depends on many factors including the technical condition and the loading of structural components of their brakes. In study [2], for example, the authors analyse stresses and temperatures occurring in the brake pad by applying SolidWorks. They propose an alternative solution to use a composite based on modified alkyl benzene resin to increase the friction coefficient.

Koptovets et al [3] provides the results of testing on freight rolling stock of industrial transport in terms of the efficient braking, as well as structural and dynamic analysis of the brake mechanism. It includes the determination of the type and parameters of the empirical dependence between the friction coefficient of the brake pad on the rolling surface of the wheel and the braking speed, as well as the determination of the kinetic characteristic of the brake for freight rolling stock of industrial transport. However, the authors did not take into account dual wedge-shaped wear of the pads of wagons, which very significantly affects the braking efficiency of industrial transport.

Kiss et al [4] presents a new friction material for brake pads, which affects the service life of the wheels of rolling stock. Particular attention is paid to the problems related to the use of modern brake materials and their influence on thermal and mechanical properties during the transmission of loading to railway wheels when braking.

Muradian et al [5,6] presents the results of operational research into the assessment of factors causing defects of thermal origin on the rolling surface of the wheel pair when interacting with composite brake pads. To prevent such defects, the authors propose using composite pads with metal inserts that will reduce their wear. During the inspection of the brake equipment of the freight train, various malfunctions of the mechanical and pneumatic parts of the brakes were detected; the inspection of the brake pads demonstrated that their wear was wedge-shaped due to touching the upper end against the rolling surface. However, the works do not describe the impact of dual wedge-shaped wear on the strength of brake pads and braking efficiency.

Mazur et al [7] analyse the operational quality indicators of cast-iron and composite brake pads used on various types of rolling stock. The study describes some negative factors of composite pads and explains how they affect the environment and cause damage to rolling surfaces of wheels of rolling stock.

A lot of studies on the use of composite brake pads for rolling stock are dedicated primarily to the issues of traffic safety and environment protection. Therefore, the reduction in operational costs for the railway industry often means that brake pads are considered as a product that is often purchased at the lowest price if it performs satisfactorily. However, this may not imply the lowest operating costs, and the choice of friction material may have a direct impact on the service life of the wheel, the replacement of which is usually much more expensive than that of other car assemblies [8].

Mazur and Sirenko [9] compare the quality indicators and performance characteristics of cast-iron moulded and composite brake pads on the basis of publications overview. They also describe some disadvantages in using composite pads, such as, low thermal conductivity, which causes a thermal impact on the rolling surface of the wheel of rolling stock. This leads to an increase in the maintenance costs for wheel pairs. Another significant disadvantage is the fact that the manufacturing specifications, standards and technical documents do not include the list of components of the rubber mixture and their chemical composition; it contradicts the current legislation of Ukraine and makes it impossible to control these substances. However, the article does not mention the expenses caused by abnormal wear of composite brake pads, which can occur during movement of freight rolling stock when brakes are not applied.

Sharma et al [10] describe various friction braking devices used to reduce the resistance of movement. It is noted that friction brake mechanisms, in which composite brake pads are used, adversely affect the rolling surface of the wheel due to very high temperatures in the pad-wheel friction area, so preference is given to disc brakes.

Some scientists focus on studying disc brakes, calculating the strength of their elements, monitoring their operation, as well as calculating temperature modes for some parts of brake systems used for rolling stock [11, 12]. When friction brakes are applied, thermal energy is generated in the contact area of tribotechnical bodies; this energy is dissipated by forced convection, conduction and radiation from the exposed brake surfaces rotating during the train movement. Day et al [13, 14] state that overheated tribotechnical pairs can cause failures in the brake system, thus it can lead to violation of traffic safety. In this regard, significant theoretical research is being done to reduce the temperature during braking according to movement speeds and brake disc designs.

Other studies [15,16], aimed at introducing modern materials into the design of tribotechnical units, substantiate the effectiveness of their application in modern rolling stock; this makes it possible to increase the speed of movement, the axial load, the efficiency of the brake system, etc. But, at the same time, there are a number of problems associated with abnormal wear of brake pads in wagons that need to be solved. And the problems associated with wear of brake pads and wheels of freight rolling stock actually exist [17]. In this regard, the work related to improvements of the lever transmission elements of wagons to protect the movement of freight trains by increasing the efficiency of their brakes is being carried out.

The analysis of literature allows us to conclude that the issues of dual wedge-shaped wear of composite brake pads used in the brake systems of bogies in Ukraine at present are relevant and require research and development.

The objective of the research was to determine the thermal stress state of the composite brake pad used for a wagon at operational loads. To achieve this objective the following tasks were set:

- to investigate the thermal stress state of the composite brake pad with rated parameters;

- to investigate the thermal stress state of the composite brake pad with dual wedge-shaped wear.

2. The research into the thermal stress state of the composite brake pad with rated parameters

The thermal stress state of the brake pad at operation loading modes was determined using the strength calculation. It was carried out with the finite element methods in SolidWorks Simulation [18].

A composite brake pad 2TP-11 was chosen as the prototype. The main characteristics of the pad are given in table 1.

Table 1. The main characteristics of the brake pad.

Parameter	Measurement unit	Value
Overall dimensions		
– width	mm	80^{+2}_{-1}
– thickness	mm	$65^{+5}_{-1.5}$
Mass		
– for asbestos pad	kg	3.15±0.2
– for asbestos-free pad	kg	3.2±0.25

The spatial model of the pad was built in accordance with its album of drawings in SolidWorks (figure 2). The finite-element model of the pad was built with spatial isoparametic tetrahedrons with four Jacobian points (figure 3). The optimal number of elements of the model was determined by the graphoanalytic method. The mesh was based on the curvature. The number of elements in the mesh was 2829, and nodes – 12219. The maximum element size of the mesh was 15 mm and the minimal element size was 6.2 mm. The number of elements in the circle was 9. The element size gain ratio was 1.6.

The model was fixed by the back plate in the area adjacent to the shoe. The material of the pad was composite with linear elastic orthotropic properties. At the same time, the compressive

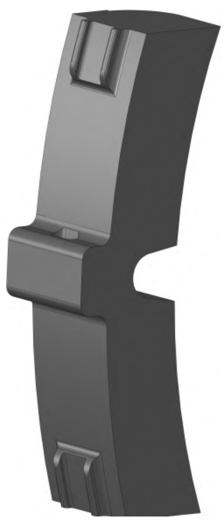

Figure 2. Spatial model of the brake pad.

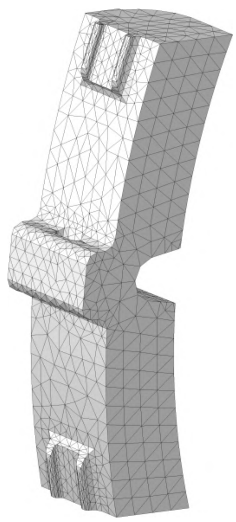

Figure 3. Finite-element model of the brake pad.

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strength of the material was taken equal to 15 MPa, and the tensile strength was taken close to zero.

The design diagram of the pad is shown in figure 4. It included the horizontal load P_H to the working part of the pad, the value of which was taken according to the operational mode of the air distributor: 41.69 – freight mode; 34.34 – medium mode; 17.5 kN – empty mode [19]. Also, the model included the friction force P_{FR} determined by the formula:

$$P_{FR} = P_H \cdot \mu, \tag{1}$$

where μ – the friction coefficient ($\mu = 0.34...0.65$).

The authors took into account the average value of the friction coefficient $\mu = 0.5$.

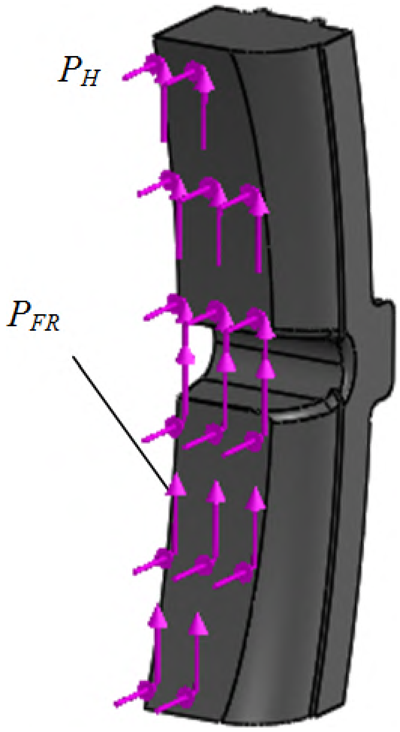


Figure 4. Design diagram of the pad.

It's worth noting that the pad suffered the temperature load during braking. The temperature on the rolling surface of the wheel in operation could be determined using the analytical expression [20]:

$$\Delta\tau_n = \frac{q_T}{\alpha_0} \cdot \left[1 - e^{-\frac{2\cdot\alpha_0}{\sqrt{\pi\cdot\lambda\cdot\gamma\cdot c}}\cdot\sqrt{t}\cdot\left(1-\frac{2}{3}\cdot\frac{t}{t_B}\right)}\right], \tag{2}$$

where q_T – the density of heat flux, kcal/(m^2 · °C); α_0 – the coefficient of heat transfer to the environment; λ – the thermal conductivity coefficient, kcal/(m^2 · °C); γ – the specific weight, kN/m^3); c – the specific heat capacity, kcal/(kgf · °C); t_B – the braking time until a complete stop, s.

The highest temperature during braking on the wheel surface was reached in the middle of this process $t = 0.5 \cdot t_B$:

$$\Delta\tau_{n\max} = \frac{q_T}{\alpha_0} \cdot \left[1 - e^{-0.9433\cdot\frac{\alpha_0}{\sqrt{\pi\cdot\lambda\cdot\gamma\cdot c}}\cdot\sqrt{t_B}}\right]. \tag{3}$$

The temperature on the surface of the wheel when the train stopped was $t = t_B$:

$$\Delta\tau_{nK} = \frac{q_T}{\alpha_0} \cdot \left[1 - e^{-0.667 \cdot \frac{\alpha_0}{\sqrt{\pi \cdot \lambda \cdot \gamma \cdot c}} \cdot \sqrt{t_B}}\right]. \tag{4}$$

The temperature as it was set during braking (at a constant speed):

$$\Delta\tau_{n\infty} = \frac{q_T}{\alpha_0} \cdot \left[1 - e^{-2 \cdot \frac{\alpha_0}{\sqrt{\pi \cdot \lambda \cdot \gamma \cdot c}} \cdot \sqrt{t_B}}\right]. \tag{5}$$

The following input parameters were used in the calculation: $q_T = 25.8$ kcal/(m^2 · °C); $\alpha_0 = 0.03$; $\lambda = 2 \cdot 10^{-4}$ kcal/(m^2 · °C); $\gamma = 2.2 \cdot 10^3$ kN/m^3; $c = 0.28$ kcal/(kgf · °C); $t_B = 120$ s.

By analysing dependencies (2) – (5), can conclude that the temperature on the pad surface was constantly changing by braking time. Therefore, when calculating the strength of the pad, the maximum allowable value of the temperature load P_T was taken into account. This load was applied to the working surface of the pad (figure 5) and was taken equal to 400 °C. The effect of this temperature on the pad material was estimated by introducing a coefficient of thermal expansion of $4.1 \cdot 10^{-6}\ K^{-1}$ for the material.

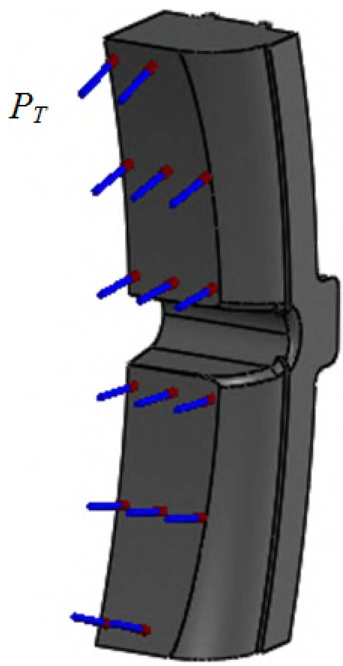


Figure 5. Diagram of the temperature loading applied to the pad.

Since the material mentioned had a small tensile strength and no yield strength, the strength calculation was made according to the Mohr–Coulomb criterion, i.e., the theory of internal friction. It is known that this criterion predicts failures if the simultaneous action of the maximum principle tensile stress and the minimum principle compression stress exceeds the appropriate stress limits [19].

In the case of a uniaxial stress state, the law of strength had the form [21]:

$$\tau \leq (\sigma - U) \cdot tg\varphi + c, \tag{6}$$

where τ and σ – the tangential and normal stresses acting at some point of the base; U – the pressure in the pore liquid; φ – the internal friction angle, c – the specific adhesion.

For the case of the spatial state, the formula took the form:

$$\frac{\sigma_1 - \sigma_3}{\sigma_1 + \sigma_3 + 2 \cdot c \cdot ctg\varphi} \leq \sin\varphi; \tag{7}$$

$$\sigma_1 > \sigma_2 > \sigma_3, \tag{8}$$

where σ_1, σ_2 and σ_3 – the principal stresses.

In accordance with this criterion, failures were predicted in the following cases:

- the principal tensile stresses were greater than zero $\sigma_1 > 0$ and $\sigma_3 > 0$. In this case, the failure criterion was taken into account if the principal stress exceeded the boundary tensile stress, i.e. $\sigma_1 > \sigma$;
- the principal compression stresses were less than zero $\sigma_1 < 0$ and $\sigma_3 < 0$. In this case, the failure criterion was taken into account if the admissible principal stress exceeded the boundary compression stress, i.e. $\sigma_1 > \sigma$;
- the principal tensile stress was $\sigma_1 > 0$, and principal compression stress was $\sigma_3 < 0$. The failure criterion in this case was:

$$\frac{\sigma_1}{\sigma} + \frac{\sigma_3}{\sigma_s} > 1; \tag{9}$$

The results of the calculations are given in figures 6 – 8.

By analysing the results obtained, we can conclude that the maximum stresses occur in the upper part of the pad in the contact area between the back plate and the side plate; they amount to 14.9 MPa and do not exceed the permissible values (15 MPa [22]).

3. The research into the thermal stress state of the composite brake pad with dual wedge-shaped wear

The strength of the brake pad was calculated and its dual wedge-shaped wear was taken into account. The calculation was made for the composite brake pad with dual wedge-shaped wear used for the wagon with a mileage of 63400 km. According to the measurements (figure 9, a), the

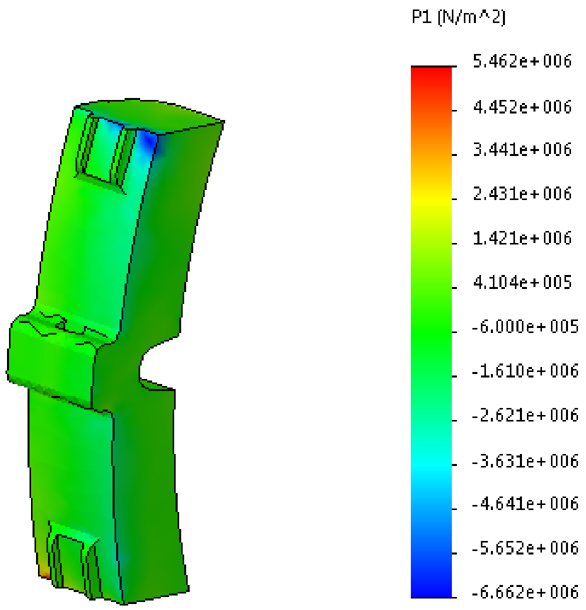


Figure 6. First principal stress in the pad.

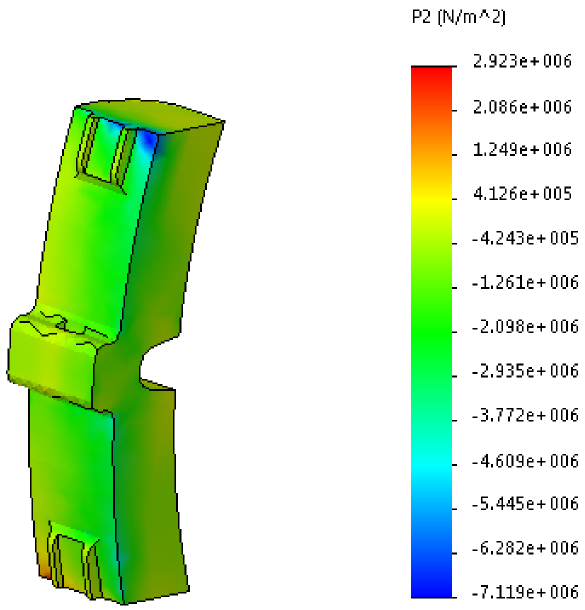


Figure 7. Second principal stress in the pad.

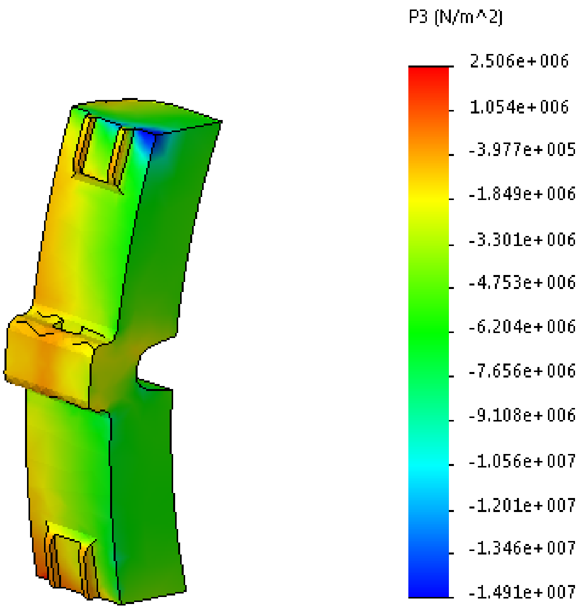
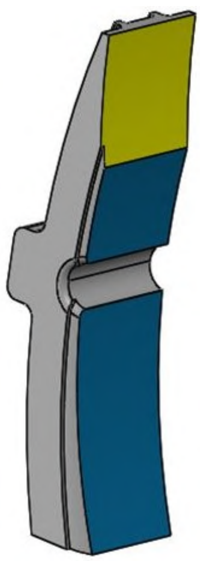


Figure 8. Third principal stress in the pad.

(*a*)



(*b*)

Figure 9. General view of the composite brake pad with dual wedge-shaped wear: (*a*) measurements of the geometric parameters of the pad to determine abnormal wear; (*b*) spatial model.

pad had the following abnormal wear characteristics: thickness at the upper end $\Delta_U = 10$ mm; thickness along the borderline of the plates $\Delta_{BL} = 27$ mm; thickness at the bottom end $\Delta_B = 20$ mm and length of harmful abrasion at the top of the pad $l_H = 85$ mm.

The design diagram of the pad included the loads identical to those shown in figure 10 and figure 11.

The finite-element model of the brake pad with wear consisted of 5429 elements and 24502 nodes (figure 12). The maximum element size of the mesh was 12 mm and the minimal element size was 2.4 mm. The number of elements in the circle was 9. The element size gain ratio was

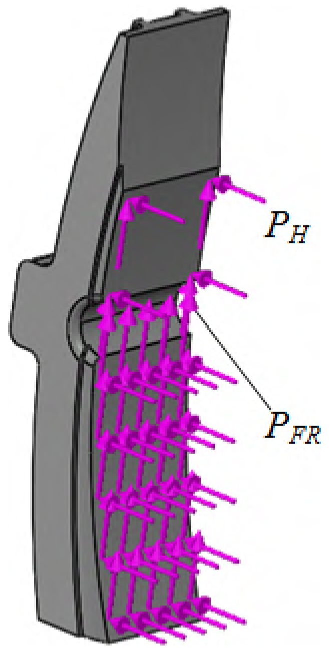


Figure 10. Design diagram of the pad with wear.

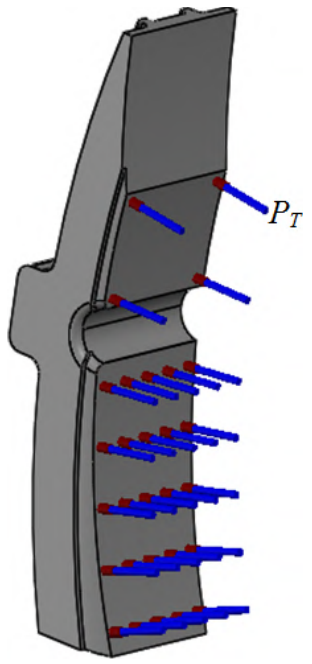


Figure 11. Diagram of the temperature load applied to the pad with wear.

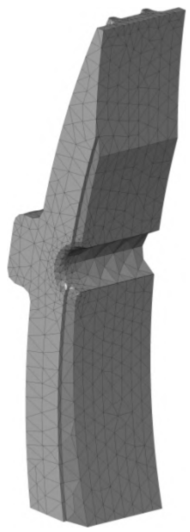


Figure 12. Finite-element model of the brake pad with wear.

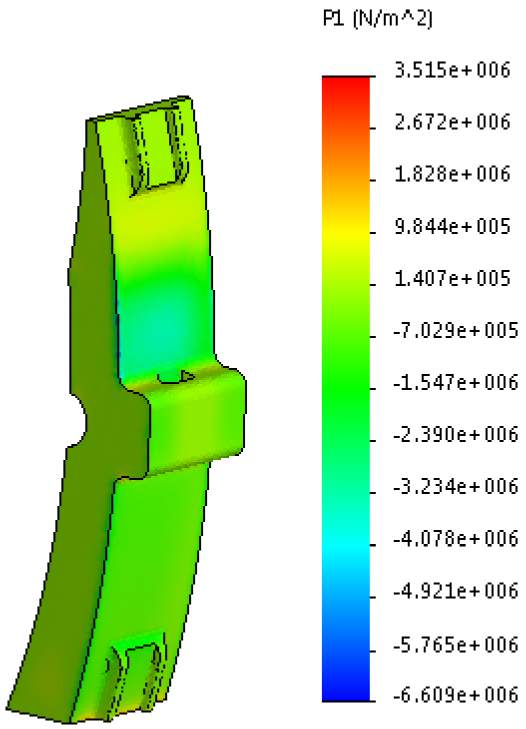


Figure 13. First principal stress in the pad with wears.

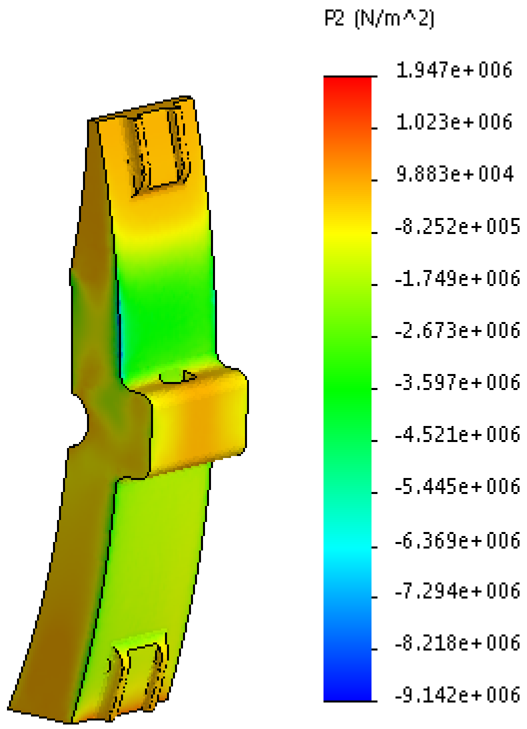


Figure 14. Second principal stress in the pad with wears.

1.6.

The results of the calculations are given in figures 13 – 15. The maximum stresses were recorded in the back plate of the pad and amounted to 18.7 MPa (third principal stress); they exceeded the permissible values by 19.8%.

The distribution of stresses along the upper part of the brake pad is shown in figure 16.

The graph presents the stresses by module. Their numerical values were determined using the probing option in SolidWorks Simulation. From this figure it can be concluded that the maximum stresses occur at a height of 135 – 140 mm from the top of the pad.

4. Conclusions

The research deals with the thermal stress state of the composite brake pad with rated parameters. It has been found that the maximum stresses (third principal stress) occur in the upper part of the pad in the contact area between the back plate and the side plate; they amount to 14.9 MPa and do not exceed the permissible values (15 MPa). The maximum stress distribution in the pad is explained by the fact that the frictional force is taken as upward in the calculation. When pointing it downward, which may be typical for the opposite triangle of the bogie, the dislocation of the stresses is opposite to the resulting loading diagram.

The research includes the thermal stress state of the composite brake pad with dual wedge-shaped wear. The maximum stresses occur in the back plate of the pad and amount to 18.7 MPa (third principal stress); they exceed the permissible values by 19.8%. This is explained by the fact that the useful area of the pad decreases, and, accordingly, its loading increases.

The research conducted proves the negative impact of dual wedge-shaped wear not only on the braking efficiency, but also on the strength of brake pads. This requires the development of measures aimed at eliminating this wear.

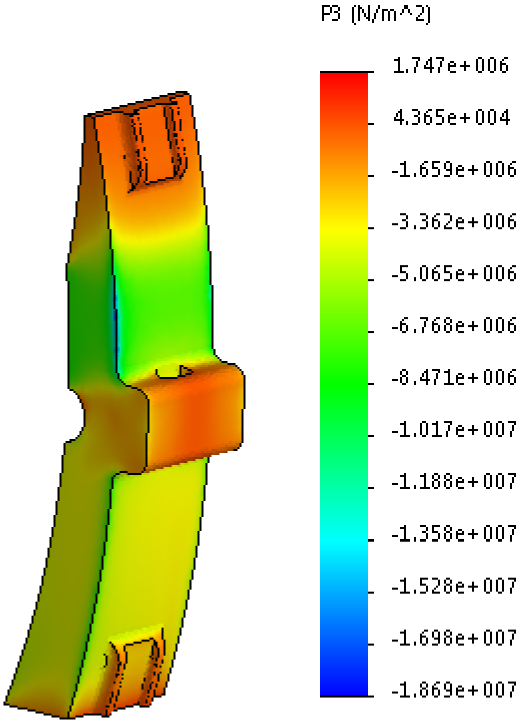


Figure 15. Third principal stress in the pad with wears.

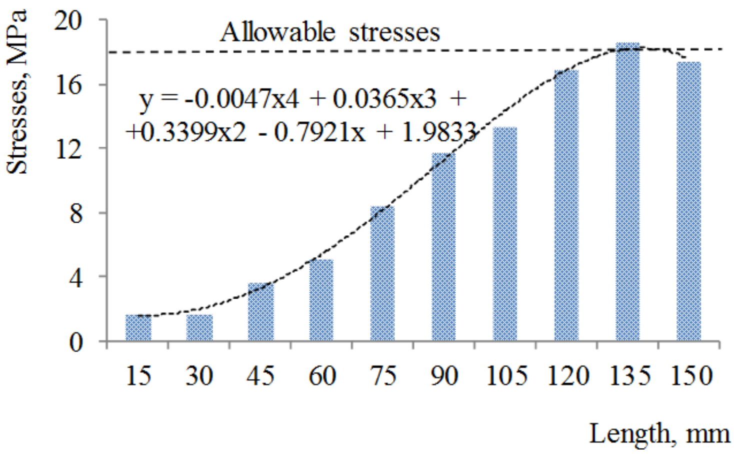


Figure 16. Distribution of stresses along the upper part of the brake pad.

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References

[1] Panchenko S, Vatulia G, Lovska A, Ravlyuk V, Elyazov I and Huseynov I 2022 *EUREKA: Physics and Engineering* (6) 45–55 URL https://doi.org/10.21303/2461-4262.2022.002638
[2] Chaubey A O and Raut A A 2015 *IPASJ International Journal of Mechani-*

cal Engineering **3**(12) 37–41 URL https://www.scribd.com/document/294429738/Failure-Analysis-of-Brake-Shoe-in-Indian-Railway-Wagon

[3] Koptovets O, Haddad J S, Brovko D, Posunko L and Tykhonenko V 2020 *E3S Web Conference* **201** 01033 URL https://doi.org/10.1051/e3sconf/202020101033

[4] Kiss I, Cioata V, Alexa V and Ratiu S 2016 *ANNALS of Faculty Engineering Hunedoara – International Journal of Engineering* **XIV**(4) 231–240 URL http://web.archive.org/web/20200719070926/http://annals.fih.upt.ro/pdf-full/2016/ANNALS-2016-4-37.pdf

[5] Muradian L, Shaposhnyk V and Shykunov O 2021 *Bulletin of railway transport certification* (3(67)) 5–15

[6] Muradyan L, Shaposhnik V and Vinstrot B 2015 *Lokomotiv-inform* (7(8)) 20–22

[7] Mazur V L, Naidek V L and Popov Y S 2021 *Metal and Casting Journal of Ukraine* **29**(2) 30–39 URL https://doi.org/10.15407/steelcast2021.02.080

[8] Hodges T 2012 *International Railway Journal* URL https://www.railjournal.com/in_depth/a-life-cycle-approach-to-braking-costs/

[9] Mazur V L and Sirenko K A 2022 *Processy lit'â* **149**(3) 54–62 URL https://doi.org/10.15407/plit2022.03.054

[10] Sharma R C, Dhingra M and Pathak R K 2015 *International Journal of Engineering Research & Technology* **4**(1) 206–211 URL https://www.ijert.org/braking-systems-in-railway-vehicles

[11] Gupta V, Saini K, Garg A K, Krishan G and Parkash O 2016 *Asian Review of Mechanical Engineering* **5**(1) 18–23 URL https://ojs.trp.org.in/index.php/arme/article/view/2409

[12] Sarip S 2013 *International Journal of Applied Physics and Mathematics* **3**(1) 52–58 URL https://doi.org/10.7763/IJAPM.2013.V3.173

[13] Day A J, Harding P R J and Newcomb T P 1979 *Proceedings of the Institution of Mechanical Engineers* **193**(1) 401–406 URL https://doi.org/10.1243/PIME_PROC_1979_193_043_02

[14] Day A J 1991 *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering* **205**(2) 127–136 URL https://doi.org/10.1243/PIME_PROC_1991_205_161_02

[15] Craciun C and Cruceanu C 2007 *Brakes for railway vehicles. Laboratory guidance* (Bucharest: Matrix Rom Publishing House)

[16] Cruceanu C 2012 Train Braking *Reliability and Safety in Railway* ed Perpinya X (Rijeka: InTech) chap 2 URL https://doi.org/10.5772/37552

[17] Kiss I 2016 *Acta Technica Corviniensis – Bulletin of Engineering* **9**(3) 77–84 URL https://www.proquest.com/docview/1806389126

[18] Aliamovskii A A 2010 *COSMOSWorks. Osnovy rascheta konstruktcii na prochnost v srede SolidWorks [COSMOSWorks. Fundamentals of strength analysis of structures in the SolidWorks environment]* (Moscow: DKM) URL https://ru.pdfdrive.com/cosmosworks-%D0%9E%D1%81%D0%BD%D0%BE%D0%B2%D1%8B-%D1%80%D0%B0%D1%81%D1%87%D0%B5%D1%82%D0%B0-%D0%BA%D0%BE%D0%BD%D1%81%D1%82%D1%80%D1%83%D0%BA%D1%86%D0%B8%D0%B9-%D0%BD%D0%B0-%D0%BF%D1%80%D0%BE%D1%87%D0%BD%D0%BE%D1%81%D1%82%D1%8C-%D0%B2-%D1%81%D1%80%D0%B5%D0%B4%D0%B5-solidworks-e176101423.html

[19] 2004 URL https://dpzl.dp.ua/files/CT-CV-CL-0015_Instrukciya_po_ekspluatacii_tormozov-ukr-_2004.pdf

[20] Martynov I E, Ravlyuk V H and Afanasenko I M 2014 *Rozrakhunky teplovykh rezhymiv pry halmuvanni : metodychni vkazivky do vykonannia kontrolnoi roboty z dystsypliny "Nova halmova tekhnika"* (Kharkiv: UkrDAZT) URL http://lib.kart.edu.ua/handle/123456789/7048

[21] Shvets V B, Boiko I P, Vynnykov Y L, Zotsenko M L, Petrakov O O, Solodiankin O V, Shapoval V H, Shashenko O M and Bida S V 2014 *Mekhanika gruntiv. Osnovy ta fundamenty* 2nd ed (Dnipropetrovsk: Porohy) URL https://ir.nmu.org.ua/handle/123456789/146421

[22] 2001 Technical conditions TU U 6-05495978.017

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Energy potential of mining transport at mines of Kyrgyzstan located at high altitude

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Energy potential of mining transport at mines of Kyrgyzstan located at high altitude

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Abstract. Review and Justify use of new alternative way of gold ore transportation on high altitude mining operations in Kyrgyzstan in prime purpose of the study. Glaciers of Kyrgyzstan are main source of fresh water supply in Central Asia. Local ecosystem preservation is important part of metal mining in Kyrgyzstan and specific needs of nomads should be taken in the account. Novelty of study is preliminary assessment of mine in Kyrgyzstan for potential gravity energy by loading and dumping point's GPS coordinates are taken on site and review of appropriate technologies for ore transportation in order to reduce carbon emissions. Aerial ropeway specific energy consumption formula and recuperating ropeway system from previous studies are reviewed and used in study. Improvement of existing mine operations by improving transportation practices should be further studied. The design and maintenance of haul roads may allow to reduce diesel fuel consumption by 10% and more. Preliminary potential energy for recuperation by aerial ropeway application in Jerooy and Jamgyr gold mines of Kyrgyzstan are identified. Energy recuperating aerial ropeway system with fuel cells can be strategically long-term preferred solution for mines in Kyrgyzstan located in high altitude.

1. Introduction

About 45% of all glaciers in Central Asia are situated on the territory of Kyrgyzstan. They are the major source of water-supply for rivers, and forecasts of their condition are of particular concern due to the effects of global climate change. Glaciers and snowfields on the mountain tops are of great importance in the regulation for water supply and regulation of natural features of the region. There are 8200 glaciers with total area of 8169, 4 square kilometers within Kyrgyzstan, occupying 4.2% of the country. Water resources of the glaciers of Kyrgyzstan are estimated at 650 km^3 [1].

17 deposits gold deposits are on the state balance nowadays which are: Kumtor, Jerooy, Jamgyr, Makmal, Soltonsary, Terekskoe, Kuru-Tegerek, Taldybulak Levoberezhny, Kurandzhailyau, Terekkan, Terek-Mezhplastovoe, Mironovskoe, Abshyr, Ishtamberdy, Dolpran, Perevalnoe, Chalkuiryuk-Akdzhylga. Officially registered reserves of gold are 1055.256t [2].

As 90% of country territory is located in mountain landscape. Number of gold deposits located above 3000 meters above sea level on visible proximity to glaciers and significant snow walls. Lower hills and valleys are valuable assets for local nomad for cattle and crop farming. Mineral mining in mountain countries like Kyrgyzstan typically has advantages that processing plants can be located bellow mine. This opens opportunity to use potential gravity energy of gold ore are being transported down to processing plant. The main purpose of this paper is to review and evaluate the latest technologies to reduce carbon emission to reduce impact of mining operation to environment.

According to the International Energy Agency mining companies should reduce their carbon emissions by 58% by 2050 compared with 2010 [3]. Meeting this target is going to be the big challenge considering that demand for minerals is growing as the population is growing. The globe is running out high grade deposits and mining low grade ore means task to move more tonnage to longer distances and increase mineral mining at remote locations such us mining in mountains at high altitude.

Nowadays there are solutions for significant reduction of carbon emission while transportation of materials from equipment manufacturers are available. Assessment of running mining operations for emission reduction opportunities must be one of the key elements in this initiative. As transportation costs can take 40-60% of overall mining costs improvement of haul road design and maintenance can reduce consumption diesel fuel and as well. If the rolling resistance is higher than that used during mine planning, the trucks are unable to achieve the expected productivity [4].

There are 4 types of hybrid technology under study by developers: 1. Battery hybrid powertrain; 2. Supercapacitor hybrid powertrain; 3. Hydraulic hybrid powertrain; 4. Compressed-air hybrid powertrain. The power saving of mining hybrid haul truck studied by Chun Jin and others in 2019 [5]. Recycling of lithium batteries are studied by Rahman and Afroz in 2016 [6]. Hydro-Pneumatic Energy Storage System for Hybrid Mining Trucks was studied by Yi and other in 2022 [7]. Niuric and others studied the trolley assist diesel-electric AC trucks in 2009 [8].

Mtu Rolls-Royce engineers' states 220 tonnes payload mining haul truck traveling downhill potentially can recuperate 22% of energy and on loaded downhill application up to 54% of energy can be recuperated. Fuel performance simulation on 220 tonns payload truck shows 29% less green-house gas emission for factory installed hybrid system [9].

The foregoing allows us to conclude that the research for alternative types of transportation of mining material in the development of high-altitude deposits is an actual problem.

The purpose of this research was to find and justify an alternative method of transporting minerals in the high-mountain mines of the Kyrgyz Republic, providing a reduction in energy consumption, a reduction in emissions of harmful gases, and an improvement in the technical and economic indicators of transportation of minerals.

Based on the analysis of existing operations in high-altitude mines, two technological schemes for transporting ore were selected for further study: the use of aerial ropeway and the use of dump trucks with diesel drives.

At the same time, the following main tasks were solved: ensuring cheaper transportation of ore, saving expensive diesel fuel, improving the environmental situation (reducing harmful emissions).

1.1. Related works

Climate change [1] and greenhouse gas emission assessment [10] is vital aspect of further development of energy profile [11] and mineral resource industry of Kyrgyzstan [2]. As transportation of materials is one of the main cost structures of mining operation decarbonization of this process [3] has strategical importance. Improving haul road maintenance and design [4] can be the first action to be considered by miners in their decarbonization plans. Mining trucks widely used in open pit mines have the potential to recover around 30% of potential energy [5] by hybrid trucks technologies. Increasing lithium battery capacity and availability makes feasible use of hybrid and electric trucks in mining industry [12]. Recycling of lithium batteries has great meaning for sustainable resource saving initiative. More than 90% of Cobalt (Co) can be extracted from composition of $CoSO_4$ [6]. Novel energy storage technologies for hybrid trucks is being studied such us the hydro-pneumatic hybrid truck with optimized scheme reduces its fuel consumption and carbon emission by 23.57 kg/day and 72.12 kg/day respectively compare with reverse dragging scheme [7]. For any open pit mines dipper than 150 meters trolley assist diesel-electric mining trucks can be seriously considered [8]. 54% of potential energy can be recuperated on system introduced by Mtu Rolls-Royce [9]. For mine located on mountain terrain conditions aerial rope way can be long term solution. Self-propelled wagons as one of the possible solutions [13] to increase productivity of rope ways can be considered depending on mine's conditions. Recuperation of potential gravity [14] energy can further increase return on investment in aerial rope ways in Kyrgyzstan mines.

1.2. Purpose
Transportation costs may reach 50-70% of overall mining costs. The present work aims to study status of ore transportation from mine sites to processing plans in mines located in Kyrgyzstan at high altitude mountain conditions and possibility to use alternative technologies in order to reduce costs of transportation as well as carbon emission and impact to environment.

To achieve this goal study covers two areas:

1. Review and asses modern alternative technologies for application on mine sites of Kyrgyzstan.
2. Identify potential energy and carbon emission savings while application various transportation technologies.

2. Research methodology
When conducting research, a comprehensive methodology was used, including the analysis of literary sources, the experience of mining operations in high altitude mountains, the study of the terrain of the Jerooy and Jamgyr mines of the Kyrgyz Republic, a technical and economic assessment of the proposed new technological and economic solutions.

The technology of transporting mining material by dump trucks with a diesel drive was adopted as the base for the research. As alternative schemes, the transportation of rock mass by aerial ropeway.

2.1. Methodology and analysis
Aerial ropeway application can be optimal solution for miners in Kyrgyzstan as long terms solution. It can help to reduce impact to glacier ecology and wildlife as well as increase safety for personal. Jerooy and Jamgyr gold mines have significant energy recuperation potential as ore processing plants are located at lower altitude than mine sites.

Table 1 shows the ore loading and dumping point's GPS locations that were taken on site.

Table 1. Ore loading and dumping points of Jerooy and Jamgyr mine sites.

Locations	Title	Jerooy mine data		Jamgyr mine data	
		Coordinates	Altitude	Coordinates	Altitude
Loading point – A	h_1	42°17'32"N 72°45'34"E	3150 m	42°11'13"N 71°32'59"E	3240 m
Dumping point - B	h_2	42°23'34"N 72°43'34"E	2062 m	42°10'32"N 71°31'45"E	2988 m

Table 2 shows potential energy data for related mine sites.

Table 2. Annual potential enegry data of Jerooy and Jamgyr mine sites.

Parameters	Title	Units of measure	Jerooy mine value	Jamgyr mine value
Ore transportation target per year	m	tonnes	1 300 000	150 000
Height of transportation	H	meter	1088	252
Acceleration of gravity	g	meters per second	9,81	9,81
Potential energy	E	Mega Joules	13 875 264	370 818

Potential energy is calculated by formula (1):

$$E = mg(h_1 - h_2). \tag{1}$$

2.2. Calculation methodology of energy consumption of ropeway

Specific energy consumption is the amount of energy consumed by a ropeway for transporting cargo. The specific energy consumption of the ropeway can be calculated by formula (2) [13]. Specific energy consumption for traditional design (with haul rope)

$$e_{HR} = 2\left(1 + k_m + \frac{q_T \lambda}{m_1}\right)(fL + H)\,g, \tag{2}$$

where k_m is the wagon loading coefficient, $k_m = m_0/m_1$; q_T is the distributed load taking into account the weight of rope and wagons; λ is the wagon hanging spacing; m_1 is the total weight of cargo; f is the resistance factor of wagon movement and haul rope; L is the track length in the plan; g is the acceleration of gravity; m_0 is the wagon weight (empty).

Specific energy consuption for ropeway carriyng loaded wagons down the hill can be calculated by formula (3):

$$e_{HR} = 2\left(1 + \frac{m_0}{m_1} + \frac{q_T \lambda}{m_1}\right)(fL + H)\,g. \tag{3}$$

3. Results and discussion

Jerroy and Jamgyr mine operations demonstarate sugnificant potential for energy recuperation. It is importante to evaluate ways to recuperate potential gravity energy and store it.

Figure 1 describes the way recuperative cableway system with fuel cells works [14]. Unit (10) serves for transportation of the load using a skyline (1), mainly for skidding, which uses gravity of the carriage and load to run an electric generator (8) with the help of a winding device (3) and a clutch (5), and voltage from electric generator (8) helps electrolysis of water in fuel cells (10), where oxygen and hydrogen and produced, and consequently they synthesize in fuel cells (10) into water when pulling an carriage up the hill, and at the same time, voltage is produced, and it is transmitted through the switch (13) into an electric motor (9), it runs the winding device (3) using a clutch (6) and it helps to move the carriage down the hill.

The recuperative cableway system with fuel cells can be a practical solution to recuperate energy of cargo traveling down the hill. As Lithium-Ion batteries become widely available at reasonable cost they can can be used as fuel cells in mentioned solution to store recuperated energy. Recycling of Lithium-Ion batteries are very important issue for environment. Recovery of valuable metals from used Lithium-Ion batteries are studied by Wang et al [12].

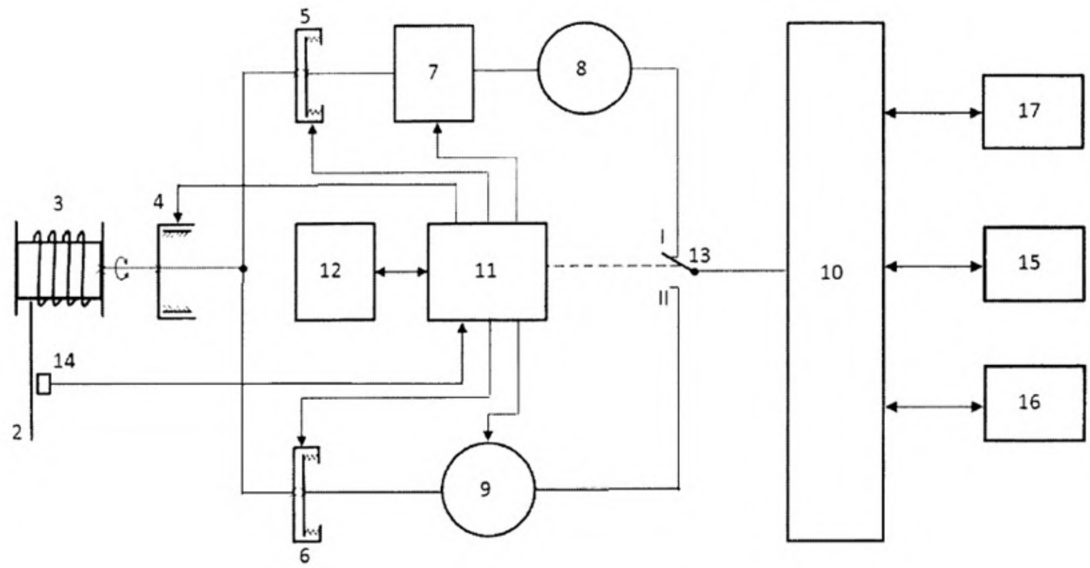

Figure 1. The recuperative cableway system with fuel cells.

The system for transportation of the load, mainly for downhill storage (1), is characterized obtaining energy for the system running from fuel cells (10).

According to claim 1, the system is characterized by the winding device (3) is connected with the electric generator (8) connected with fuel cells using electric conductors in the phase of gravitational approaching.

The system is characterized by that the fuel cell (10) is connected by electric conductors with the electric motor (9), which is connected to the winding device (3) in the phase of moving carriage down the hill.

Results of cycle timing study on site displayed productivity and CO_2 emission estimation because of common way of ore transportation by diesel engine driven truck on one of the gold mines in Kyrgyzstan (table 3).

CO_2 emission calculated by formula (4) [10]:

$$CO_2(t) = \sum VK, \tag{4}$$

where K is the Diesel fuel burn CO_2 emission coefficient CO_2 EF kg CO_2/l – 2.65; V is the Diesel fuel consumption.

Performance of arial ropeway implemented in Cerattepe copper mine in Turkiye described in [15]. Diesel equivalent consumption is estimated as per ration of 0.88 US gallons per 37.95 kWt/hour (table 4).

Specific equivalent fuel consumption of aerial ropeway per one ton at Cerattepe mine in 0.6 liters per ton. Whereas the same parameter for diesel driven dump truck is 2 liters per ton. Thus, CO_2 emission with aerial rope way is 3.3 times lower from fuel consumption point of view. Study does not consist of CO_2 emission and energy consumption for auxiliary processes such as maintenance and repair of equipment and haul road and ropeway.

The mining industry is increasing its electrification processes to meet global demand to reduce carbon emissions. As per International Energy Agency Kyrgyzstan has around 90% of total electricity generation in hydro-based making it one the county with highest shares of renewable electricity in the world. However only about 10% of hydro energy potential has been developed [11].

Table 3. Site performance results of ore transportation by on-high way truck in gold mine in Kyrgyzstan.

Parameters	Units of measure	Value
Payload of truck	tonnes	25
Engine power	kWt	295
Distance	kilometer	35
Average time per trip	hour	2.75
Average fuel consumption per trip	liter	50
Productivity per truck	tonnes per hour	9.09
Fuel consumption	liters per hour	18.18
Average operating time	motor hours	6500
Annual CO_2 emission	kilogram	311968.8
Horizontal length on plan	meters	11749
Vertical fall	meter	-1088
Established power per produced ton	kWt per tons per hour	32.45
Specific fuel consumption	liters per ton per kilometer	2

Table 4. Performance of arial ropeway implemented in Cerattepe copper mine.

Parameters	Units of measure	Value
Productivity	tonnes per hour	60
Motor power	kWt	414
Horizontal length on plan	meters	4471
Vertical fall	meters	-1515
Established power per produced tonn	kWt per tons per hour	6.9
Equivalent of diesel fuel consumption	liter per hour	36.38
Specific equivalent fuel consumption	liter per ton	0.6

4. Conclusions

In this research various drive systems of transportation technologies and their performance in open mine operations located in high altitudes in Kyrgyz Republic.

Main results and conclusions are in following:

1. Analyses of operational performance of aerial ropeway and diesel driven dump trucks shows that aerial ropeway in 3.3 times more energy efficient. Transportation path on aerial ropeway is 3-7 times shorter in compare with haul road for dump trucks operation.
2. Cycle timing study on various mines shows that equivalent diesel fuel consumption of aerial ropeway in high altitude mine conditions can be only 0.6 liters per ton, for transport systems with diesel driven dump truck can reach 2 liters per ton.

Considering amount of renewable energy share in electricity generation of Kyrgyzstan use of aerial ropeways in mining can be significant contribution to environment and local ecosystems.

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References

[1] Balbakova F, Alamanov A and Lipka O 2015 Climate change vulnerability assessment for Central Tian-Shan, Kyrgyzstan Tech. rep. WWF, the global conservation organization Moscow URL https://doi.org/10.13140/RG.2.1.1696.5523

[2] Rogalsky A 2019 Report on Classification of Energy and Mineral Resources and its Management in the Kyrgyz Republic Tech. rep. United Nations Economic Commission for Europe URL https://unece.org/DAM/energy/se/pdfs/UNFC/proj/unfc_ca/Report_Class_EMR_KG_Arkady_Rogalsky.pdf

[3] Muralidharan R, Kirk T and Blank T K 2019 Pulling the Weight of Heavy Truck Decarbonization: Exploring Pathways to Decarbonize Bulk Material Hauling in Mining Tech. rep. Rocky Mountain Institute URL https://rmi.org/insight/pulling-the-weight-of-heavy-truck-decarbonization/

[4] Visser A T 2015 *Journal of the Southern African Institute of Mining and Metallurgy* **115**(11) 993–999 URL http://www.scielo.org.za/scielo.php?script=sci_arttext&pid=S2225-62532015001100010

[5] Jin C, Yi T, Shen Y, Khajepour A and Meng Q 2019 *IET Intelligent Transport Systems* **13**(1) 201–208 URL https://doi.org/10.1049/iet-its.2018.5085

[6] Rahman A and Afroz R 2017 *International Journal of Energy Technology and Policy* **13**(3) 278–291 URL https://www.inderscienceonline.com/doi/abs/10.1504/IJETP.2017.084497

[7] Yi T, Jin C, Gao L, Hong J and Liu Y 2022 *Machines* **10**(1) 22 ISSN 2075-1702 URL https://doi.org/10.3390/machines10010022

[8] Nurić S, Nurić A and Brčaninović M 2009 *Journal of Mining and Metallurgy A: Mining* **45**(1) 78–87 URL https://scindeks.ceon.rs/article.aspx?artid=1450-59590901078N

[9] Rolls-Royce Power Systems AG 2022 Hybrid Haul Truck: Sustainable Power Webinar Series. Improve productivity and reduce emissions URL https://industrial.mtu-solutions.com/hybrid-haul-truck-webinar

[10] Breisinger M 2012 Greenhouse gas assessment emissions methodology VPS/ESG Technical note IDB-TN-455 Inter-American Development Bank URL https://publications.iadb.org/en/greenhouse-gas-assessment-emissions-methodology

[11] 2021 Kyrgyz Republic Energy Profile Tech. rep. International Energy Agency URL https://www.iea.org/reports/kyrgyzstan-energy-profile

[12] Wang K, Zhang G and Luo M 2022 *Separations* **9**(9) 259 ISSN 2297-8739 URL https://doi.org/10.3390/separations9090259

[13] Raksha S V, Kuropiatnyk O S and Krasnoshchok O L 2019 *Science and Transport Progress* (6(84)) 60–71 URL https://doi.org/10.15802/stp2019/195601

[14] Stollmann V, Ilcík S, Suchomel J and Smal P 2012 Recuperative cableway system with fuel cells Patent WO 2012/074494 A1 World Intellectual property Organization URL https://patents.google.com/patent/US20130241315/ar

[15] Doppelmayr Group 2022 Materialseilbahn Cerattepe URL https://www.doppelmayr.com/en/reference-projects/reference-project-mgd-m-cerattepe/

Pathophysiological mechanisms of adaptation of the mucosa of the gastric cardia to portal hypertension

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Pathophysiological mechanisms of adaptation of the mucosa of the gastric cardia to portal hypertension

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Abstract. The model of before- and intrahepatic blockage of the portal system was proposed. Modeling of before-hepatic blockage of the portal system after development of toxic liver dystrophy lead to formation of the liver cirrhosis with stable portal hypertension. Gastritis with signs of hyperplastic and atrophy processes of the mucosa, formation of erosia, inflammatory infiltration of intermediate tissue and rebuilding of the glandulae were the basis of morphological changes of gastric mucosa in rats with experimental before- and intrahepatic portal blockage. Transformation of the cardiac mucosa with expressed polymorphism occured in the patients with the portal liver cirrhosis. Dystrophic and necrobiotic changes typical of hepatic gastropathy with signs of acute or chronic gastritis, formation of inflammatory infiltrates and rebuilding of the cardial mucosa into intestinal type were established microscopically. It is possible to believe that a widening of the veins leads to venous hyperemia and stasis in the portal hypertension. Therefore the morphology of the gastric mucosa was disturbed. It was accompanied bythe indurate changes and cellular destruction with erosia formation. These erosia may be a cause of rupture of the gastric mucosa in strong vomiting in Mallory-Weiss syndrome. This hypothesis needs clinic and experimental study in the future.

1. Introduction

In economically developed countries, cirrhosis of the liver is one of the six main causes of death in patients aged 35 to 60 years. Geographic features of mortality from cirrhosis among men and women are similar [1].

Significant geographic differences in the incidence and mortality of liver cirrhosis are observed in developing and developed regions of the world. This is due to the different level of the economy and the development of medicine [2].

Globally, an estimated 58 million people have chronic hepatitis C virus infection, with about 1.5 million new infections occurring per year [3].

One of the goals of sustainable development in Ukraine is good health and well-being to ensure healthy lifestyles and promote well-being for all, regardless of age. To solve this goal, one of the tasks is to reduce the premature mortality of the population by a quarter, including through the introduction of innovative approaches to the diagnosis of diseases [4].

Therefore the actuality for clinical and experimental researches of etiopathogenetic mechanisms of development and elimination of liver diseases and their complications. The basis of experimental research is working out the methods of the liver cirrhosis modeling, acute and chronic liver insufficiency developed with before, and intrahepatic portal blockage.

The known methods of modeling of before-hepatic blockage of the portal system include the ligation of the portal vein and its intrahepatic branches or to apply cuff on the portal vein decreasing its diameter [5, 6]. The animals die in hours after ligation of the main trunk of the portal vein, and in days (4 – 10) after ligation of its branches. The cirrhotic changes in the liver have no time to appear [6, 7]. It is not possible to apply muff on the portal vein for dosage change of its diameter for small laboratory animals (rats). The portal hypertension developed in such method of modeling in dogs after some months [6]. Opie [8] proposed to model the

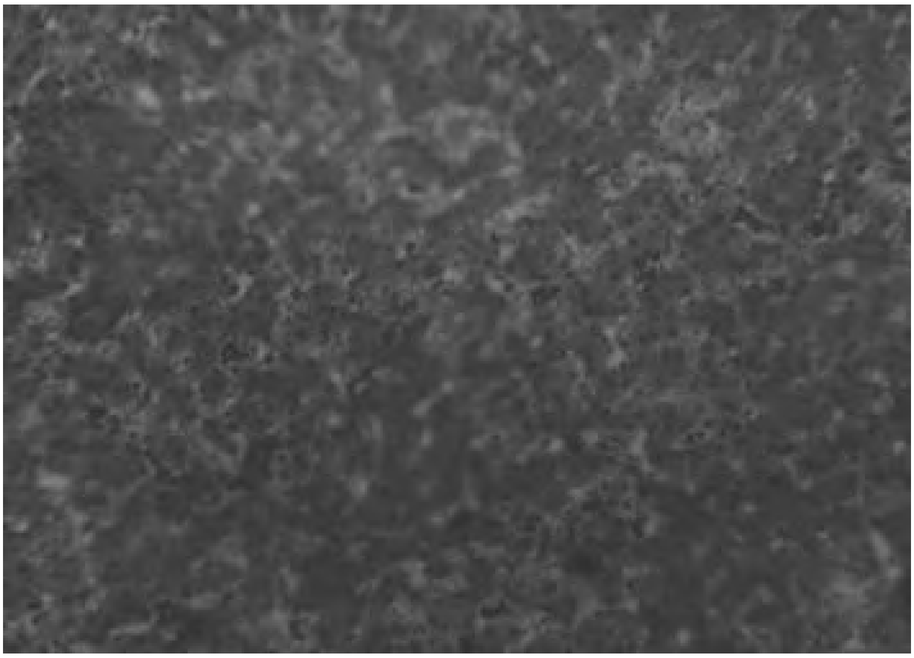

Figure 1. The liver acquired a view of Muscat in the 20^{th} day of experiment.

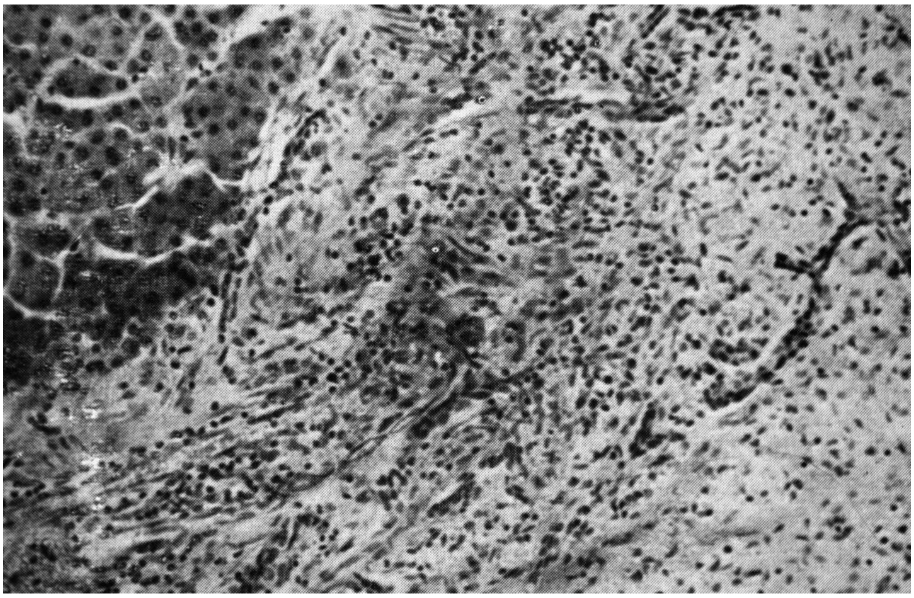

Figure 2. Liver cirrhosis formation in the 30^{th} day of experiment.

intrahepatic portal blockage by injection of chloroform into the jugular vein in a combination of injection of culture of E. coli. The liver cirrhosis developed in 23 days [6, 7].

The famous methods of modeling of before- and intrahepatic blockage of the portal system have low reproduction, it is not possible to do it in small laboratory animals. It has some technical difficulties and low economic effect.

Therefore the purpose of the research includes to elaborate some effective, easy reproductive model of before- and intrahepatic blockage of the portal system. The main purpose of the research was to study pathophysiological mechanisms of adaptation of the mucosa of the gastric cardia to portal hypertension in experiment at rats and in patients.

2. Experimental procedures

The first step of the research was carried out in 20 healthy adult Wistar rats with weights between 240 – 280 gram in period from September to December. Intrahepatic portal blockage was modeled by intraperitoneal injection of Chloroform 0.5 ml/kg two times a week. Before-hepatic portal blockage was modeled by injection of warm (40 – 5°C) Glycerinum 0.1 ml/100 gram from 20^{th} day after the beginning of Chloroform injection. The pressure in the portal vein was measured by surgical polygraphe "Salyut" before and after Glycerinum injection, and also for 20^{th}, 25^{th} and 30^{th} days after the first Chloroform injection. Then the animals were taken out of experiment. The preparations were fixed in 10% Formaline solution on phosphate buffer pH 7.2–7.4 with the temperature +4°C. Histological sections with thickness 10, 15 and 20 mkm were colored by Hematoxilin-eosin, described and photoed by digital photocamera Mustek MDC-3000.

The pressure in the portal vein was measured and analogous histological researches of stomach preparations were done in 5 false operated animals (the control group). A maintenance of the animals including feeding, anaesthesia and euthanasia were carried out according to the rules regimenting the experiments on animals.

The second step of the research was done in 20 preparations of the cardia of the gastric mucosa in patients with the portal liver cirrhosis. The areas of the cardia of the gastric mucosa were taken within 30–45 minutes after patient's death. The preparations were fixed in fresh 10% Formaline solution in phosphate buffer pH 7.2–7.4 at temperature +4°C. Histological sections with thickness 10, 15 and 20 mkm were colored by hematoxilin-eosin, studied under microscope, described and photos made. The statistical analysis of results was done.

The experimental procedures outlined in this section were conducted in strict adherence to a comprehensive set of ethical guidelines, including both international and national regulations. We have provided a more detailed account of the ethical rules and procedures followed during our experiments to ensure transparency and compliance with the ethical standards governing research in Ukraine and internationally.

Our research was conducted in accordance with the regulatory requirements of Ukraine and the norms widely accepted in international research practice. Specifically, we adhered to the following ethical frameworks:

1. We conducted our research in compliance with the principles outlined in the ICH GCP (International Conference on Harmonisation Good Clinical Practice) guidelines, which ensure the ethical conduct of clinical trials and the protection of human subjects' rights and well-being.
2. We followed the principles set forth in the Declaration of Helsinki (2000), which provides guidance on ethical research involving human subjects. This declaration emphasizes the importance of informed consent, confidentiality, and the well-being of research participants.
3. Our research adhered to the provisions of the Council of Europe's Convention on Human Rights and Biomedicine, which addresses the ethical aspects of biomedicine and human

rights, including the protection of personal data.

4. To protect the privacy and identity of individuals participating in our study, we employed encryption identifiers for personal data in accordance with the Convention on the Protection of Personal Data.

All patients who participated in our study provided written informed consent. We ensured that participants were fully informed about the nature and purpose of the research, the procedures involved, potential risks, and their right to withdraw from the study at any time without consequences. Consent forms were used to document their voluntary agreement to participate.

The experiments involving animals were conducted with the utmost respect for ethical considerations. We followed established rules and regulations governing experiments on animals, including:

1. The animals were provided with appropriate nutrition to ensure their well-being throughout the experiment.
2. When necessary, anesthesia was administered to animals to minimize discomfort and pain.
3. Euthanasia procedures were carried out in strict accordance with ethical guidelines to minimize any suffering experienced by the animals.

In addition to the aforementioned international guidelines, our research also adhered to specific institutional policies and ethical review processes at our university and affiliated institutions in Ukraine. These policies encompassed a range of ethical considerations, including patient consent, animal welfare, and the handling of biological samples.

3. Results and discussion

The mean pressure in the portal vein was 58.6 $\pm$6.72 mm H_2O in rats of control group. The mean pressure in the portal vein was 78.8 $\pm$9.43 mm H_2O on the 20^{th} day after the experiment began, 223.4 $\pm$21.71 mm H_2O on the 25^{th} day, 244.0 $\pm$20.56 mm H_2O on the 30^{th} day. The mean pressure in the portal vein was 323 mm H_2O on the 30^{th} day. Weak relationship between an increasing of the portal pressure and the experiment was revealed in the 20^{th} day of experiment. There was strong direct correlation on the 25^{th} and the 30^{th} day of experiment. The coefficient of correlation and its range was 0.512 $\pm$0.43 ($p<0.1$) for study of control data and data of the 20^{th} day experiment, 0.965 $\pm$0.11 ($p<0.001$) for study of control data of the 25^{th} day experiment, 0.981 $\pm$0.17 ($p<0.001$) for study of control data and data of the 30^{th} day experiment. The strong direct correlation between an increasing of the portal pressure and term of experiment was established in comparison data between series of experiment. The coefficient of correlation and its range was 0.953 $\pm$0.28 ($p<0.001$) for study of data of the 20^{th} day and data of the 25^{th} day experiment, 0.961 $\pm$0.27 ($p<0.001$) for study of data of the 20^{th} day and data of the 30^{th} day experiment. The results of the 25^{th} day experiment were correlated with the 30^{th} day experiment (0.615 $\pm$0.45, $p<0.05$).

The changes in the liver parenchyma to be analogous to the toxic liver dystrophy was revealed. The partial necrosis of hepatocytes was discovered, mainly in the center of lobes. There was adipose dystrophy. The relief of the lobes was changed and absent in some parts of the liver. The liver acquired a view of Muscat (figure 1). It may divide some areas of the liver tissue of preserved lobulae in the 20^{th} day of experiment, showed loss of its specific view (figure 2, 3).

In the 30^{th} day of experiment some areas of the liver tissue with necrosis, adiposal distrophy, disintegration of hepatocytes with formation of indefinite blockes appeared (figure 3). Areas of increasing connective tissue were revealed. The cirrhosis began to form.

A view of superficial gastritis was established among the 80% of the rats in the 20^{th} day of experiment before Glycerinum injection. The epithelium loses its high-prismatic shape and stands more plain, the cytoplasm was pellucid. The nuclei pushed to the apical part of cell, were different by size and color. Borders between the cells were indistinct.

In 50% of rats the changes were according to gastritis with disturbance of the glandulae without atrophy. The glandulae and stroma were involved in process in these animals. There was vacuolization of the cytoplasm, necrobiosis of the cells, widening of the glandulae gap. An

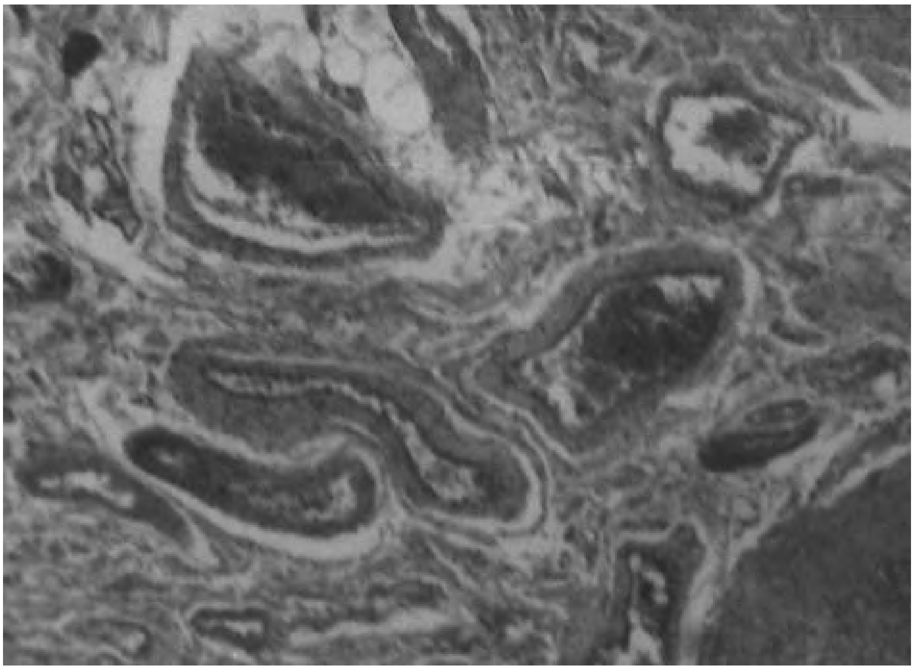

Figure 3. Expressed changes in the gastric mucosa in portal hypertension. 1 – sharply widening vein with stasis and fibrinoid necrosis of the wall. Hematoxilin-eosin. x200.

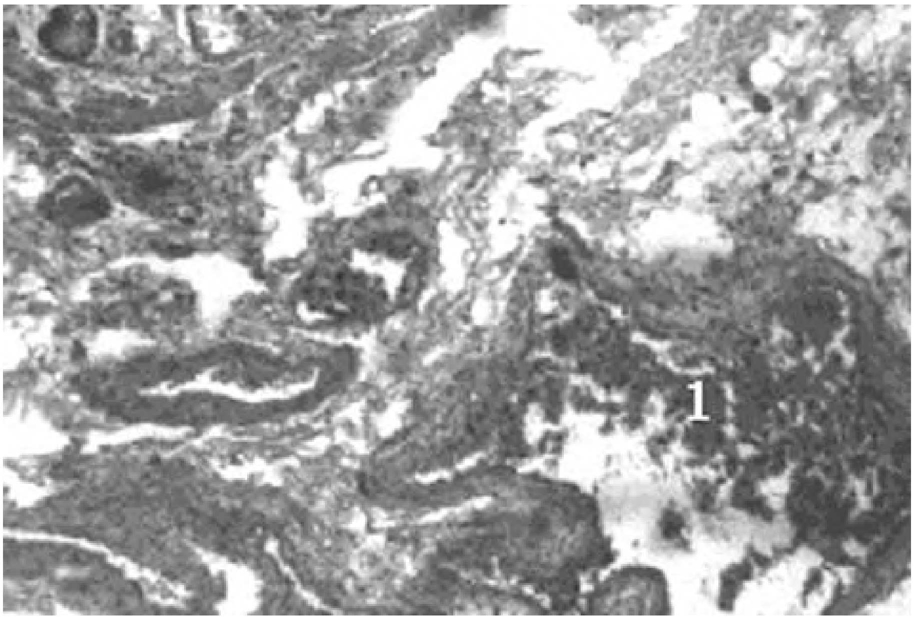

Figure 4. Erosion (arrow) of the gastric mucosa above widening veins (1). Hematoxilin-eosin. x50.

intensive cell infiltration was revealed in terminal parts of the glandulae and intermediate tissue. Basal membrane looked for thickening. Fiberous structures were increased in the stroma.

In 20% of rats changes were analogous to atrophic gastritis and thinning of the mucosa. The glandulae were conserved in small islands among the connective tissue. There were changes in the superficial epithelium and in the epithelium of the glandulae looking for intestinal metaplasia was discovered.

A lot of animals had atrophic gastritis with thinning of the mucosa in the 30^{th} day of experiment. There were multiple erosia of the mucosa in 75% of cases. The submucosal level was widened. The muscular plate of the mucosa had the areas of hypertrophy. The elastic fibers were hyperplastic.

The changes of the vessels in the submucosal level were established. The veins were widened. The epithelium was desquamoused above them. It led to formation of microerosia and erosia. The walls of the veins were thickened. Tunica propria mucosae was oedematic. It had hemorrhages and areas of polymorphic cell infiltration consisting mainly of neutrophills and eosinophills. Thre was proliferation of histiocytes and fibroblasts. Besides there were plasmatic, plump cells and lymphocytes in composition of the infiltrate.

The changes of the glandulae were oppression of formation of the mucus. the gap of the glandulae was widened. There was an increase of fiberous structures in the stroma. The quantity of the glandulae was decreased in any areas.

A death of smooth myocytes and substitution of them by the connective tissue were revealed in areas of the inflammatory infiltrates of the muscular plate in the 30^{th} day of experiment. Sometimes the muscular plate was substituted by fibrous tissue. Hemorrhages into the mucosa and the submucosa were discovered in areas of sclerosis of the tunica muscularis mucosae.

The varices of the gastric submucosal layer and atrophy of the mucosa above them were revealed in 75% all the cases.

The sharply expressed changes of the vessels of gastric cardia were established in the patients of portal hypertension. They manifested by widening, stasis, plasmatic saturation and fibrinoid necrosis of the vessel wall (figure 4).

The desquamation of superficial epithelium was increased above widening veins. It was resulted by formation of microerosion and erosion of different degree (figure 5). Microscopic picture of such type erosion was not typical and depends on stage of the process and the depth of occurrence of the blood vessels. The walls of the vessels were thick as a result of productive vasculitis. There were oedema, hemorrhages and polymorphic cell infiltration in the tunica propria mucosae. A zone of infiltration may be distributed into the submucosal and muscular layers. The neutrophills and eosinophills composed the main part of the infiltrate. There were a lot of lymphocytes, plasmatic and plump cells. A proliferation of histiocytes and fibroblasts was revealed. The lymphocytes and plasmatic cells predominated in small infiltrates (figure 6).

The formation of mucus in the gastric glandulae occured unevenly in zone of inflammatory infiltration. There were cells having significant amount of mucus granules and cells having cytoplasm filled to overflowing of mucus. Some of them lose a connection with the basal membrane and desquamated into the aperture of the glandulae. There was oppression of secret formation in the glandulae epithelium (figure 7).

A combination of dystrophic changes of the glandulae, hyperplastic and atrophic processes in the gastric mucosa with formation of erosia, an inflammatory infiltration of intermediate tissue and changes of the glandulae are the basis of morphological changes of the gastric mucosa in the patients with the portal liver cirrhosis. A cellular composition of the glandulae and a depression of their fumctional activity were connected with dystrophic changes in the gastric mucosa. Borders between the cells were indistinct. Nuclei looked like bubble with hyperchromatosis of the nuclear membrane or piknotic (figure 8).

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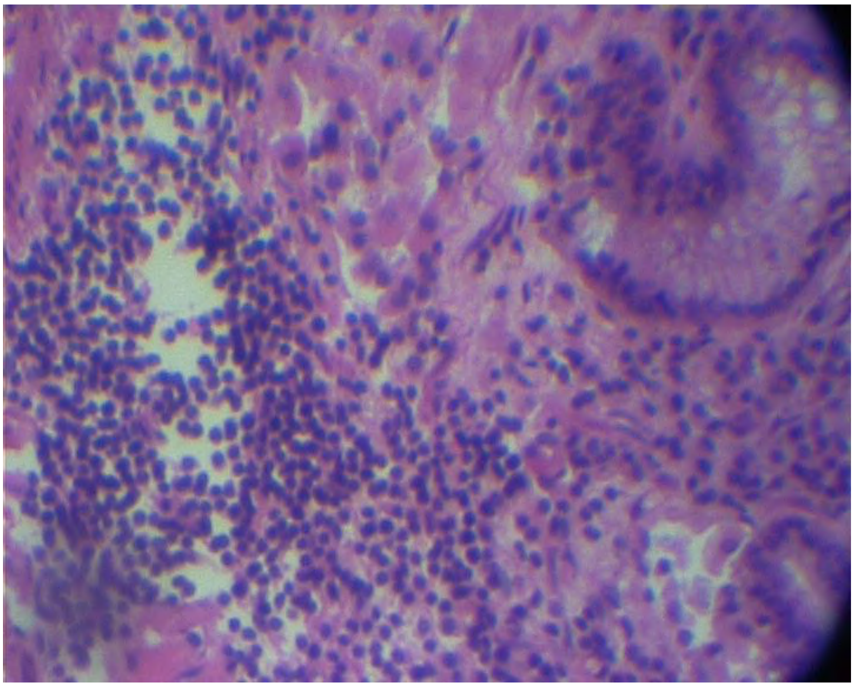

Figure 5. Zone of inflammatory infiltration. Lymphocytes and plasmatic cells predominate. Hematoxilin-eosin. x400.

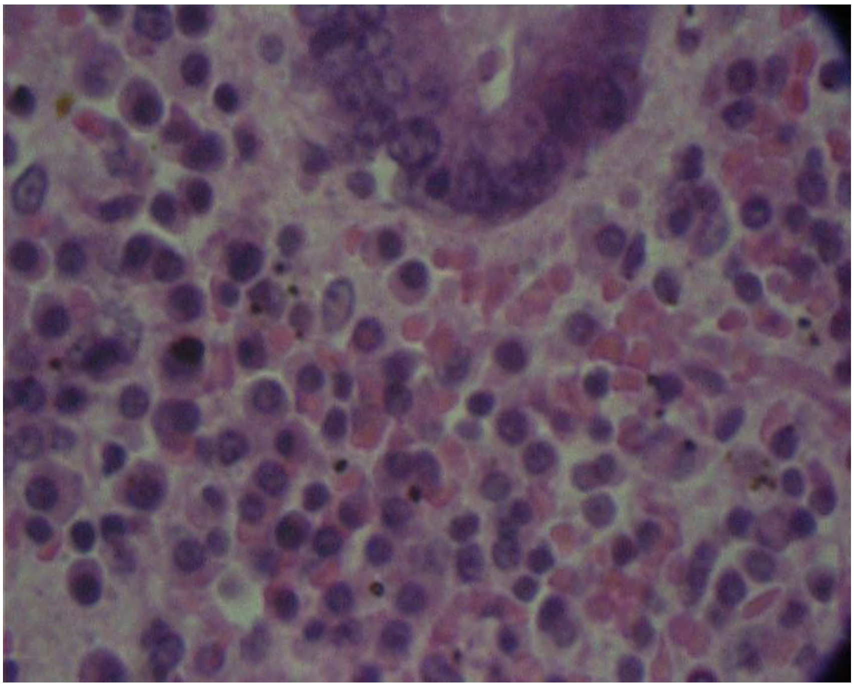

Figure 6. Oppression of secret formation in the epithelium of glandulae in zone of inflammatory infiltration. A part of glandular cell has no connection with the basal membrane, desquamation into aperture of the glandulae (arrow). Hematoxilin-eosin. x200.

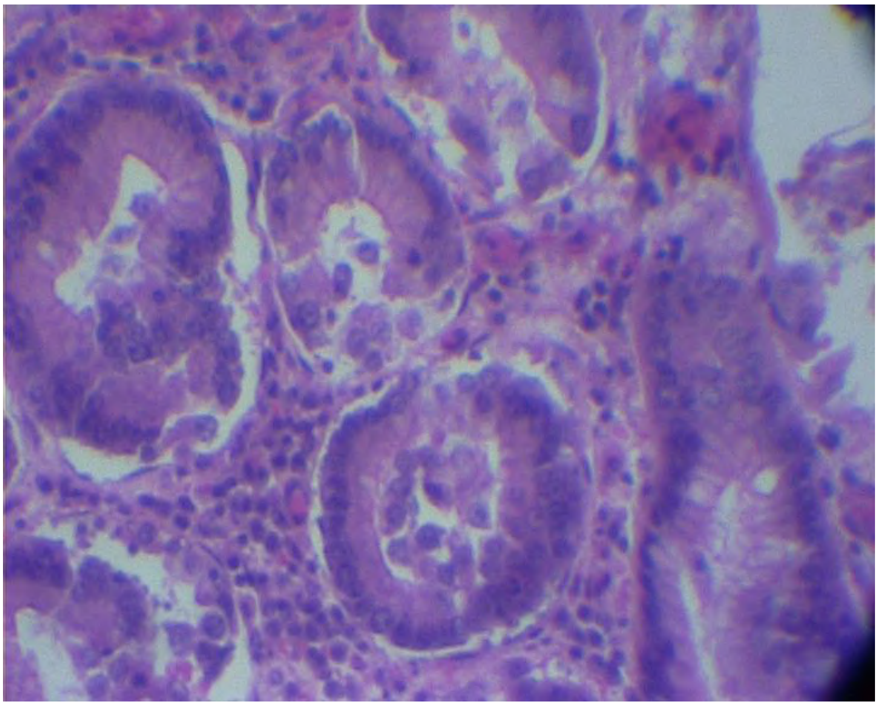

Figure 7. Borders between the cells were indistinct. Nuclei looked like bubble with hyperchromatosis of the nuclear membrane or picknotic. Hematoxilin-eosin. x400.

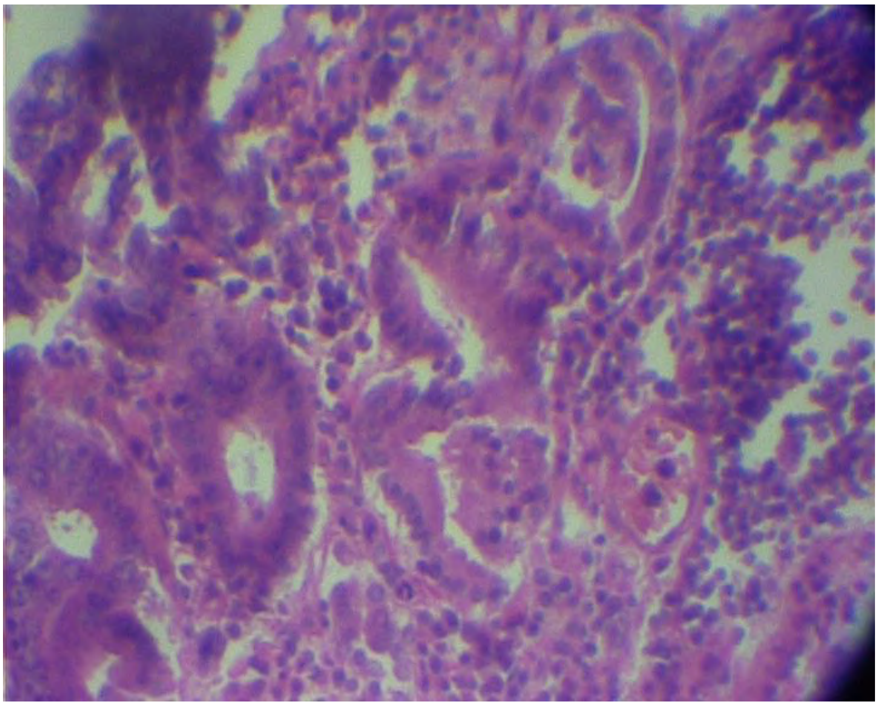

Figure 8. Polymorphic cell infiltration in the gastric holes of the tunica propria mucosae. Transformation of the gastric mucosa into intestine type. Hematoxilin-eosin. x50.

4. Conclusion

Results of the research allow to constant that it is necessary to create the complex effect for reliable modeling of the liver cirrhosis. Weak expressed portal hypertension during formation of model of the intrahepatic portal blockage was revealed. However such increasing of pressure in the portal vein was not stable. A sharp increasing of the pressure in the portal vein was established after modeling before-hepatic blockage of the portal system. Modeling of before-hepatic blockage of the portal system after development of toxic liver dystrophic lead to formation of the liver cirrhosis with stable portal hypertension. Gastritis with signs of hyperplastic and atrophy processes of the mucosa, formation of erosia, inflammatory infiltration of intermediate tissue and rebuilding of the glandulae were the basis of morphological changes of gastric mucosa in rats with experimental before- and intrahepatic portal blockage.

Transformation of the cardial mucosa with expressed polymorphism occured in the patients with the portal liver cirrhosis. Dystrophic and necrobiotic changes typical for hepatic gastropathy with signs of acute or chronic gastritis, formation of inflammatory infiltrates and rebuilding of the cardiac mucosa into intestinal type were established microscopically. It is possible to believe that a widening of the veins leads to venous hyperemia and stasis in the portal hypertension. Therefore the morphology of the gastric mucosa was disturbed. It was accompanied by the indurate changes and cellular destruction with erosia formation. These erosia may be a cause of rupture of the gastric mucosa in strong vomiting in Mallory-Weiss syndrome. This hypothesis needs clinic and experimental study in the future.

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References

[1] World Health Organization 2018 Liver cirrhosis (15+), age-standardized death rates by country URL `https://apps.who.int/gho/data/node.main.A1092`
[2] World Heath Organization 2018 *Global status report on alcohol and health 2018* ISBN 978-92-4-156563-9 URL `https://apps.who.int/iris/bitstream/handle/10665/274603/9789241565639-eng.pdf`
[3] World Heath Organization 2023 Hepatitis C URL `https://www.who.int/news-room/fact-sheets/detail/hepatitis-c`
[4] Ministry of Economic Development and Trade of Ukraine 2017 Sustainable Development Goals: Ukraine. National report URL `https://www.kmu.gov.ua/storage/app/sites/1/natsionalna-dopovid-csr-Ukrainy.pdf`
[5] Dalgat D M 1968 *Surgery* (3) 19–23
[6] Shalimov A A and Radzihovskiy A P 2003 *Atlas of operations on the digestive organs* (Kyiv: Naukova dumka)
[7] Vinogradov A A, Andreeva I V, Boiarchuk O D *et al.* 2002 *Materials of the 20th Congress of Surgeons of Ukraine* vol 2 (Ternopil: Ukrmedknyga) pp 522–523
[8] Opie E L 1901 *The American Journal of the Medical Sciences* **21** 27–42 URL `https://doi.org/10.1097/00000441-190101000-00002`